STARTERS AND REGULATORS

FOR

ELECTRIC MOTORS AND GENERATORS

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THEORY, CONSTRUCTION, AND CONNECTION

BY

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PREFACE

This work deals with the theory of starters and regulators for electrical machines, an important subject which has hitherto been somewhat neglected. As there is no work of a similar character in the English language, the translation may prove useful to those engaged in this branch of Electrical Engineering, and also to students. A general knowledge of the working of generators and motors on the part of the reader has been assumed.

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INTRODUCTORY

Electrical apparatus is subjected to mechanical and electrical stresses. The mechanical are generally not so important as the electrical stresses. The latter can be divided into the following classes :—

1. Those caused by an electric current flowing continuously through the conducting parts of the apparatus.
2. Those caused by an electric current flowing for a short time.
3. Those caused by the electric current on the breaking of the circuit.

All these cause heating, the last causes arcing also.

We will now consider how the heating or arcing can be reduced or avoided.

CHAPTER I

THE CONDUCTION OF ELECTRIC CURRENTS

THE conduction of an electric current is effected either by permanent connections (as, for instance, bolts, etc.) or by sliding contacts. The former will carry more current, the greater their conductivity or the smaller their ohmic resistance.

Assuming the current density for copper to be c_1 (either for the surface or cross-sectional area), and its conductivity to be s_1, then if the corresponding values for any other material be c_x and s_x, the maximum current density permissible will be

$$c_x = c_1 \frac{s_x}{s_1} = c_1 \frac{\rho_1}{\rho_x} \quad . \quad . \quad . \quad (1)$$

where ρ_1 and ρ_x are the specific resistances of copper and the material under consideration respectively.

In the following table are given the specific resistances * of different materials, their temperature-coefficients, and their conductivity at a temperature of 0° C.

---

* *I.e.*, the resistance of a wire of one metre length and one square millimetre cross section.

Material.	Specific resistance in ohms at 15° C.	Increase of resistance per cent. for 1° C.	Conductivity.
Aluminium	0·0308	0·388	32·35
Lead	0·2076	0·387	4·80
Iron	0·1042	0·480	9·67
Kruppin	0·8483	0·070	1·12
Copper	0·0174	0·380	57·00
Brass	0·0707	0·165	15·40
German silver	0·3010	0·036	3·14
Nickel	0·1306	0·365	7·58
Nickelin	0·45 – 0·51	0·028 – 0·019	2·2 – 1·80
Platinum...	0·0937	0·243	14·40
Zinc	0·0590	0·365	16·70

Bare copper conductors, bolts, bars, etc., may be loaded up to 2000 amps. per square inch on starters and similar apparatus. If the surface of the conductor be exposed to the air directly, and its radiating surface be comparatively large, the load might be increased to even 5000 amps. per square inch.

There is little chance of the current density of a bolt being taken too high, since it is generally limited by the contact surface of the washers and nuts, between which the connecting wire is fixed. For such contacts, and for sliding contacts of switches, starters, regulators, etc., general rules can scarcely be given. Contacts (of starters) exposed to the air, and permanent contacts on starters and switches—as, for instance, the contacts of switch in Fig. 1—may be loaded with 130 amps. per square inch.

In the following table a few values are given for current densities employed in the contact pieces of switches of different make :—

Current in ampères	200	500	1000
Sliding contact surface in sq. inches	1·4	3·5	8·3

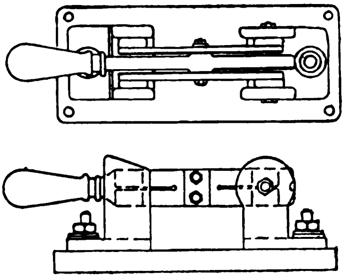

FIG. 1.

In order to secure a large contact surface, the contacts are made elastic, and in some cases either the sliding or fixed contacts are laminated.

In all cases dealt with hitherto, a current flowing constantly has been assumed ; in starters, however, there are also contacts through which the current flows for a short period only, *i.e.* for a fraction of the time of starting (which even for large motors is not more than 30 seconds). Hence these contacts can be made far smaller than those which have to carry a current continuously ; in some cases the area of the former can be made a quarter of that necessary for the latter.

The amount of heat produced is proportional to the watts absorbed ; that is, to CE or C^2R, where R is the contact resistance. In order to make the latter as small as possible, the contact should be as good as possible, and the surface of the contacts should be kept clean.

The resistance material is of special importance in the construction of such apparatus. We must here, again, make a distinction between permanent and intermittent load.

The latter will be dealt with first, being the simpler case, and occurring with starters which are used for starting only.

The time taken for starting even large motors, as stated above, does not exceed 30 seconds. The amount of heat radiated during this short period can be neglected. With this assumption, the heat produced in one second by the current C, expressed in gramme-calories, is, according to Joule's law,

$$0{\cdot}24C^2R = C^2\rho\frac{l}{a} \times 0{\cdot}24$$

where ρ = the specific resistance,
R = ohmic resistance,
l = length,
a = cross-sectional area.

Also, if ψ = the specific heat—that is, the amount of heat which is necessary to raise the temperature of one kilogram of the material 1°C—γ the specific weight, and T the rise of temperature (temperature of wire less the temperature of the surrounding atmosphere), then to produce this rise of temperature, $T\psi la\gamma$ gramme calories are required. Therefore

$$0{\cdot}24C^2\rho\frac{l}{a} = T\psi la\gamma$$

and the rise of temperature in one second will be

$$T = \frac{0{\cdot}24C^2\rho}{a^2\gamma\psi} = 0{\cdot}24\frac{\rho}{\gamma\psi}\left(\frac{C}{a}\right)^2 \quad . \quad . \quad (2)$$

where a is in square millimetres and l is in metres.

The following table shows the values of γ, ρ, ψ, and $0{\cdot}24\frac{\rho}{\gamma\psi}$ for different materials :—

	γ	ρ at 15° C.	ψ	$0{\cdot}24\frac{\rho}{\gamma\psi}$
Copper	8·96	0·0174	0·09332	0·005
German silver	8·3	0·3010	0·09710	0·089
Nickelin	9·64	0·5000	0·00795	1·566
Kruppin	8·10	0·8483	0·01228	2·44
Aluminium	2·70	0·0308	0·21800	0·1256
Platinum	21·50	0·0937	0·03230	0·369
Brass	8·70	0·0707	0·09390	0·0208
Iron wire	7·70	0·1042	0·11300	0·028

From the last column of the above table we see that the rise of temperature is highest for Kruppin, then comes Nickelin. Iron seems to be very favourable; it must not be forgotten, however, that the temperature coefficient for iron—*i.e.* its percentage rise of resistance for 1° rise of temperature—is 0·48, whereas the temperature coefficients of Kruppin and Nickelin are very small.

Soldering the connecting wires of starters on to the contacts should be avoided, such connections being generally made by means of screws (see Fig. 28); the temperature of the resistance material may then be allowed to rise as high as 200° C. during the time of starting, provided that the starter is not used frequently, so that it can cool down entirely before being used again.

Let the maximum time of starting for a motor be t (say about 30 seconds); in starting we assume the lever to be moved at a uniform speed from one contact to the next; if there are n steps or $n + 1$ contacts (Fig. 12), then the current passes through the first step for a time $\frac{t}{n}$, through the second step for $\frac{2t}{n}$, etc. Generally through the nth step for a time $\frac{nt}{n} = t$. According to formula (2) the rise of temperature in one second

$$T = 0{\cdot}24 \frac{\rho}{\gamma\psi}\left(\frac{C}{a}\right)^2$$

Let T_1 be the temperature of the room, and T_2 the maximum temperature permissible for the resistance material (200° C.), then the rise of temperature per second

$$\frac{T_2 - T_1}{t} = T = 0{\cdot}24 \frac{\rho}{\gamma\psi}\left(\frac{C}{a}\right)^2$$

Hence the cross-sectional area of the wire

$$a = \sqrt{\frac{0{\cdot}24 C^2 t \frac{\rho}{\gamma\psi}}{T_2 - T_1}}$$

or

$$a = C\sqrt{\frac{0{\cdot}24 t \frac{\rho}{\gamma\psi}}{T_2 - T_1}} = CK_1\sqrt{\frac{t}{T_2 - T_1}}$$

Where $K_1 = \sqrt{0\cdot 24 \frac{\rho}{\gamma\psi}}$. (See following table.)

Taking now a starter with n steps (Fig. 12), then for a motor which starts in time t

r_1 should have a cross-sectional area of $a_1 = CK_1 \sqrt{\frac{\frac{t}{n}}{T_2 - T_1}}$

r_2 ,, ,, ,, $a_2 = CK_1 \sqrt{\frac{\frac{2t}{n}}{T_2 - T_1}}$

Generally

r_n should have a cross-sectional area of $a_n = CK_1 \sqrt{\frac{\frac{nt}{n}}{T_2 - T_1}}$

Material.	$K_1 = \sqrt{0\cdot 24 \frac{\rho}{\gamma\psi}}$
Copper	0·071
German silver	0·298
Kruppin	1·560
Nickelin	1·250
Iron wire	0·168

It is unnecessary to make such an exact calculation for small starters ; for these the maximum cross-sectional area might be taken throughout; for large motors an exact calculation is necessary, as with such starters the saving of material may be considerable. For automatic starters in which the starting time is fixed, the cross-sectional area per step should be calculated in any case.

The maximum temperature permissible should be selected according to the work the motor has to do.

If there is any chance of the motor having to start with a heavy overload, this maximum should not be fixed too high. Two hundred degrees centigrade is the maximum temperature permissible, and should never be exceeded.

Permanent Load

In the case of coils which have to stand a permanent load, there must be no increase of temperature, for a given load, after the temperature has reached a certain limit. Hence, there must be a state of balance between heat produced and heat lost. The heat produced per second is

$$Q = 0{\cdot}24C^2R \text{ gramme-calories}$$

The heat radiated per second depends on the volume of the substance and the nature of its surface, also on the difference of temperature between the substance and the air, and finally on the velocity of the air passing the coil. It follows, therefore, that cases for enclosing resistances should always be so arranged that the stream of air can flow from below upwards. Warm air, being lighter than cold, flows upwards, so that cold air will be drawn from below into the box.

The amount of heat radiated from a substance has been determined by experiment. Dulong and Petit have found that the heat radiated per second is

$$Q = A(Q_1 + Q_2)$$

where $Q_1 = 0{\cdot}0347s(1{\cdot}0077T_1 - 1{\cdot}0077T_2)$

$Q_2 = 0{\cdot}00061(T_1 - T_2)^{1{\cdot}233}$

Q_1 is the amount of heat which is radiated per second.

Q_2, the heat which is lost by contact with the air.

s is the coefficient of radiation.

T_1, the temperature of the surface of the substance.

T_2, the temperature of the air.

A, surface area in square centimetres.

Material.	**s.**
Copper	0·16
Brass (polished)	0·26
Cast iron	3·17
Sand (fine)	3·62
Sheet iron	2·77
„ „ (polished)	0·45
Soot	4·01
Oil paint	3·71
Oil	7·24

Some types of starters and regulators have the resistance coils embedded in sand. Others have the resistance coils embedded in enamel on cast iron. Oil is also frequently utilized on account of its large coefficient of radiation.

Generally, for permanent load we have the equation—

$$\text{Heat produced} = \text{heat dissipated}$$
$$0{\cdot}24\, C^2R = Q = A(Q_1 + Q_2) = K_2A$$

where K_2 stands for the heat dissipated in one second by one square centimetre of the surface. Hence

$$C = \sqrt{\frac{AK_2}{0{\cdot}24 \times R}} = \sqrt{\frac{K_2}{0{\cdot}24}}\sqrt{\frac{A}{R}} = K\sqrt{\frac{A}{R}}$$

where K_2 and K are constant values, for a definite rise of temperature.

For a rise of temperature of 100°, which is usual for permanent loads, values for K_2 and K are given in the following table:—

	K_2	K.
Kruppin	0·0653	0·522.
Nickelin	0·0506	0·46.

From the formula $C = K\sqrt{\frac{A}{R}}$ we see that for the same cross-sectional area and length, *i.e.* same resistance $R = \rho\frac{l}{a}$, a resistance material in the form of plates can be loaded far higher than one in the form of a circular wire only; for the surface A is smaller for circular wires than for any others having an equal cross-sectional area, since for the same cross-sectional area the circle has the smallest circumference of all figures. Thus, the thinner and the wider the plates are, the more current they can carry.

In selecting a material for resistance, besides the considerations given above, its mechanical structure has to be considered. In the table given for K_1 (p. 8) the rise of temperature for a certain current is small for German silver, and since its temperature coefficient is small, it would seem to be an excellent resistance material. It has, however, the disadvantage that it becomes brittle if subjected to red heat. It further alters its structure if exposed to mechanical strain, so that, for instance, it becomes fragile if wound in coils.

The materials most frequently employed for resistances are Nickelin, Kruppin, Eureka, Rheostan, and Konstantan, and several similar alloys, manufactured especially for electrical purposes.

Intermittent Load

In the case of hoists, street railways, cranes, etc., the starter is used very frequently, and with such short intervals that there is not sufficient time for the resistance material to cool down. If such a resistance were built for momentary load it would obviously be insufficient; whereas, if built for permanent load it would be too large. In determining the dimensions of the resistance material for such an intermittent load, the shortest duration of the intervals must be considered. The difficulty is to decide what the shortest intervals for cooling down will be in the most improbable case.

The cooling down of the resistance is a function of time and the variable difference of temperature between air and the resistance material. In the above cases a smaller rise of temperature should be allowed, and that smaller, the shorter the intervals in which the starter can cool down.

In the case of hoists it is safer to assume a permanent load, since frequently the starter is switched continuously in and out, as in the case of a crane, for instance, when a load has to be lifted and lowered continuously.

The current flowing through the starter when lowering the load will in any case be smaller than the starting current, even when the motor is running as a generator for braking purposes (see Chapter V., Figs. 85 and 86); sometimes with a small load the motor has to run in series with the starting resistance in order to keep down the speed.

There is also an intermittent load on starters for motors driving machine-tools which are frequently started and stopped; in this case, however, the starting current very often exceeds the normal working current.

At the conclusion of this chapter some methods of insulating will be briefly referred to.

Insulating materials should never be subjected to a compressive strain, except in the case of washers; hence in Fig. 2 the two tubes are somewhat shorter than the distance between the two springs. An insulation bush for a terminal going through metal is shown in Fig. 3. By bevelling the two halves of the insulating bush we increase the leakage path of the current from the bolt to the metal. An insulating bush of this type, constructed of ebonite, would be sufficient for voltages up to 200 in dry rooms. The higher the voltage or the damper the atmosphere, the longer the leakage path along the surface

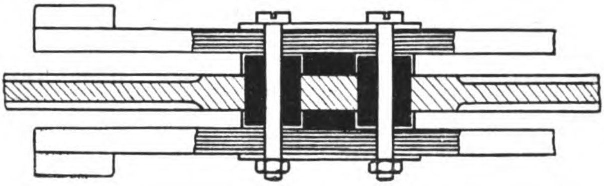

FIG. 2.

of the insulation must be made. An insulating bush

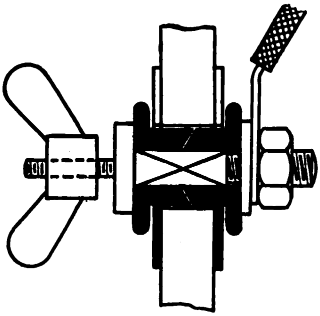

Fig. 3.

for bolts designed with this object is shown in Fig. 4. This construction would in dry rooms suffice for 2000

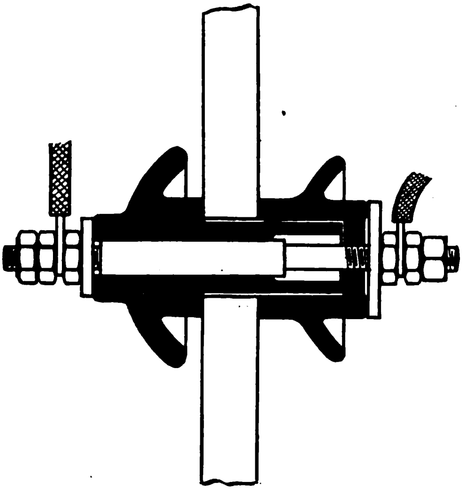

Fig. 4.

volts. For higher voltages and for very damp rooms several petticoats must be provided. In this case porcelain is employed as the insulating material.

CHAPTER II

CIRCUIT-BREAKERS AND CIRCUIT-BREAKING

In breaking an electric circuit a spark arises, the intensity of which depends on the self-induction of the circuit broken, and the effect of which is more destructive the higher the voltage and the larger the current. The spark, or rather arc, causes the metals between which the arc arises to melt. The methods of reducing or avoiding the arc can be studied best on switches, and we will deal with these first.

The simplest method of preventing the continuation of an arc is a quick break. This can, for instance, be effected by a spring (see Fig. 5) which, in switching off, is stretched until the catch N engages the bolt S on the knife; when the lever is moved further, the knife is partly drawn out of the contacts, and when finally the friction between contacts and knife becomes smaller than the

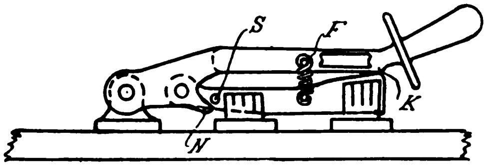

Fig. 5.

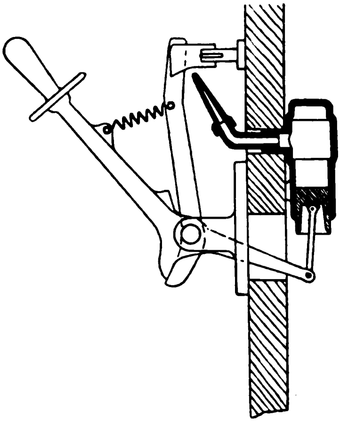

FIG 6.

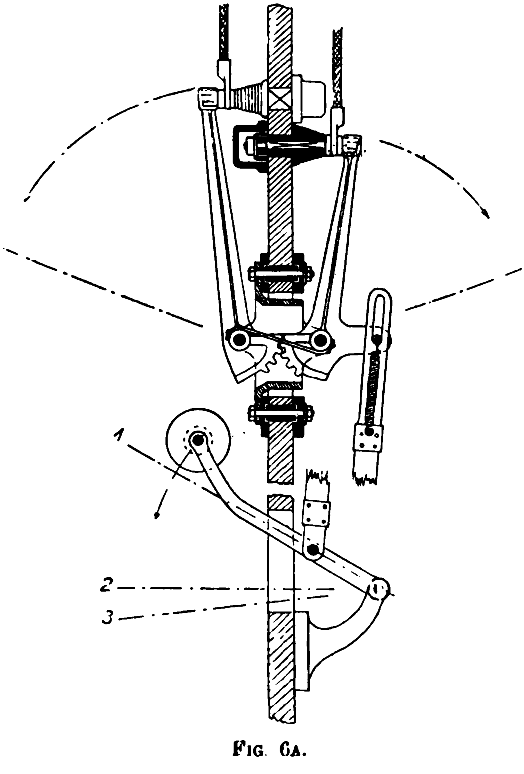

FIG. 6A.

tension on the spring, the latter closes up, drawing the knife quickly out of the contacts. The same type of quick break is shown in Figs. 6 and 6A.

Another method is to blow out the arc by means of compressed air, as shown in Fig. 6. By moving the lever of this switch, the piston of a small pump is moved upwards, thus compressing the air in the cylinder; the compressed air then blows out the arc. This construction may be employed for voltages up to 2000. The arc may also be blown out by magnets, which are placed under the arc. Such magnetic blow-outs are frequently used for controllers, to which we shall refer later on.

In the switch shown in Fig. 6A (Parshall system, employed in the London Underground Railway for 5000 volts) the arc is divided into two parts, and there is also a quick and long break provided. The effect of subdividing the arc can be observed still more distinctly in the switch shown in Fig. 7 (Schuckert-Müller system), which is used for voltages up to 6000. (The construction shown in Fig. 7 would not be

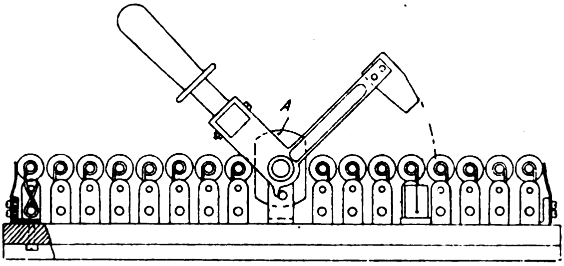

FIG. 7.

suitable for higher voltages; for this purpose it would have to be better insulated—for instance, by the use of porcelain insulators.) In switching off, the main contacts are separated first. Parallel to these, the circuit is kept closed by the rollers, as long as the metal piece which is fixed to the lever touches the rollers to its right and left with its curved sides A. When the lever reaches the position indicated in the figure, the rollers separate from each other, thus breaking the circuit in many places. Between every two rollers an arc arises, but so much heat is absorbed by the comparatively large mass of the rollers that it is soon extinguished. There is also a probability that in breaking an alternate current (for which these switches are exclusively used) some of the rollers are separated from each other just at the moment when the amplitude of the current is zero. Thirdly, the switch is made more effective by making the rollers from an easily oxidizable metal; then by the action of the arc they are covered with a non-conducting oxide, which is removed from them by friction between the rollers in closing the switch.

In Figs. 8 and 9 an arrangement is shown which prevents a continuation of the arc. In Fig. 8 (I) three currents are represented by the three arrows, 1, 2, and 3. Current 1 tends to turn current 2 in the direction of the arrow *a*, until 1 and 2 are in the same direction. Similarly current 3 tends to turn current 2 in the direction of the arrow *b*. If, therefore, conductor 2 were movable and elastic, then it would, as in Fig. 8 (II), bend upwards and move in the same direction. In Fig. 8 (IV) is shown the arrangement of a horn lightning arrestor (Siemens & Halske type). If an arc arises between the two horns, it is driven upwards by the electrodynamic action of the current explained above, and by the stream of hot air. The length of the arc

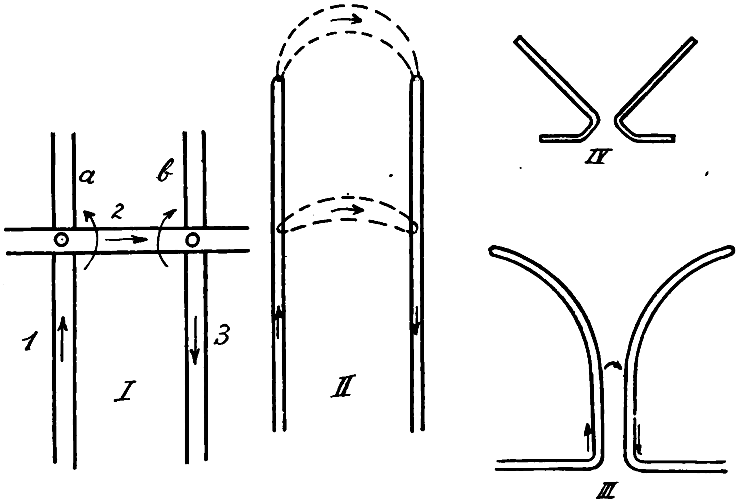

FIG. 8.

gradually increases as the distance between the horns increases, and eventually a point is reached where the arc is broken. This method is employed for lightning arrestors in high-tension plants up to 10,000 volts and above. The lowest limit is 500 volts continuous current. In this case the two horns must approach to a distance of 0·12 inches where the horns are parallel (see Fig. 8, III). This method is very often made use of in high-tension switches. One application of it is shown in Fig. 9, which is an illustration of a high-tension switch (Bertram type). Through the front panel of the switchboard a lever projects, which can be fixed in either of the positions marked "on" (III), "off" (II), or "dead" (I).

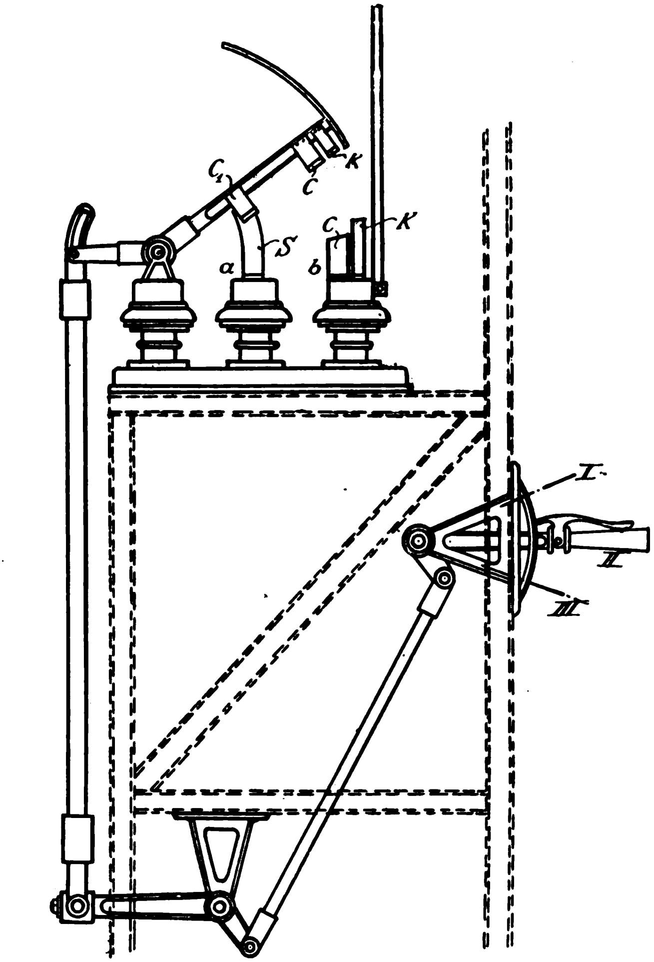

Fig. 9.

The position shown in the figure is the "off" position. One pole is connected with *a*, and the other one with *b*. In switching off, the sliding contact C_1 does not leave the bar S. The contact is first broken at C, then at the carbon contacts K, so that the arc is formed between the straight and circular horns. This arc will not be extinguished suddenly, but gradually, thus forming a damping resistance for the generator. In order to cut the current off the switch altogether, for renewing the carbons or for any other purpose, the front lever is moved to the highest position, marked "dead;" the contact C_1 then leaves S. The circular shape of one of the horns makes the extinguishing of the arc independent of the speed of switching off; the horns of this switch, as well as those of the Siemens' lightning arrestor, are little affected by the arc.

A simple method of destroying the arc is to form a vacuum in a cylinder in which the break takes place. The fixed contact is inserted in the bottom of the cylinder, while the movable contact forms a tight-fitting piston.

Metals between which the arc arises should have a very high fusing temperature, so that only very small quantities of conducting metal vapour are produced. Thus copper or brass contacts are sometimes provided with platinum tips. Very frequently the auxiliary contacts are made of carbon (see Fig. 10). The arc can only arise between the carbons in this construction, since these are in contact before the knife is drawn from the contacts, and are separated only when the knife has come entirely out of the main contacts.

The edges of the carbons are generally rounded, with the object of causing the arc to leave at any place, other than the contact surface. For the same reason, the edges of the knives and contacts of metal switches are rounded, as shown in Fig. 11, for the arc is produced between those surfaces which are separated last.

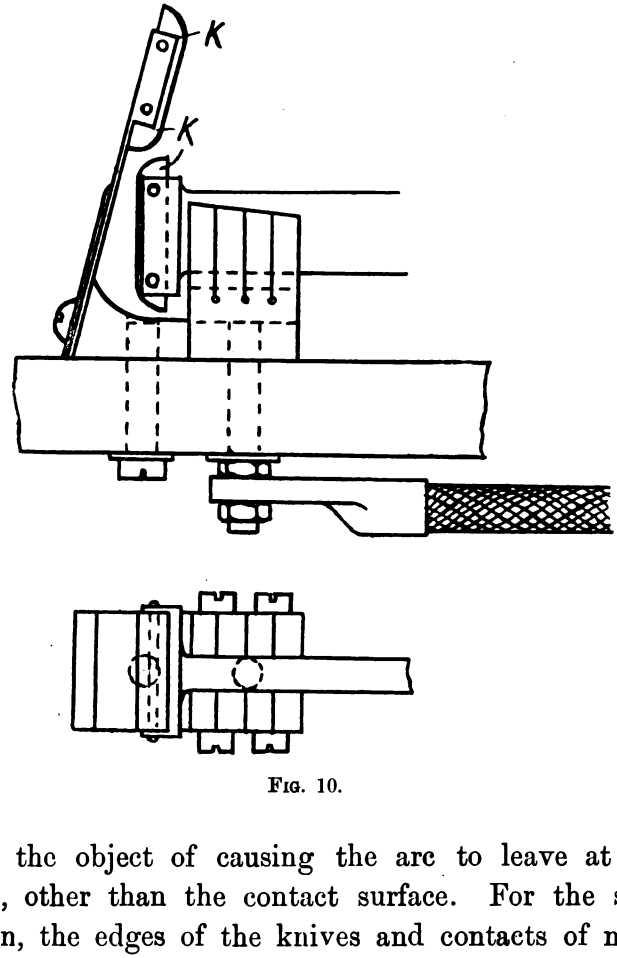

Fig. 10.

We shall see later on that by means of a special

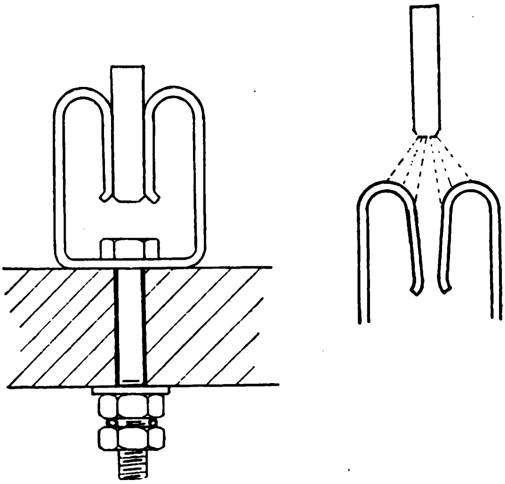

FIG. 11.

method of connecting starters and regulators, arcs can be almost entirely avoided.

CHAPTER III

THEORY OF STARTERS

In this chapter starters for continuous-current motors will be dealt with first.

If a starter has to be designed for a shunt motor (as in Fig. 12), we can allow a starting current c_1, which is a little larger than the normal current c. Assuming now that the motor would start with the current c_1 on the first step, then, as there is no back E.M.F. at the moment of starting, we have the equation

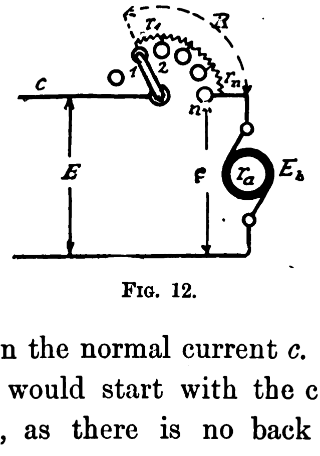

FIG. 12.

$$c_1 = \frac{E}{R + r_a} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

where $R = r_1 + r_2 + r_3 + \ . \ . \ . \ + r_n$ is the total resistance of the starter, and r_a the resistance of the armature. After a short time the armature reaches the speed which is normal for the first contact. The current then falls to its normal value c, and the armature rotating in its normal field produces a back E.M.F. = E_{b_1}, corresponding to its low speed. We have then

$$c = \frac{E - E_{b_1}}{R + r_a} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

When we now move the lever of the starter on to contact 2, then at that moment the back E.M.F. of the armature is still E_{b_1}; since, however, the resistance has been diminished by r_1, the current will increase. Hence every time the lever is moved from one contact on to the next there will be a rush of current. On moving the lever to a new contact, the current increases, but falls immediately in the same ratio as the back E.M.F. of the armature increases. The current c corresponds to the torque which has to be exerted by the armature. To produce this current the back E.M.F. of the armature must increase as the starting resistance is cut out. The rush of current should not exceed the starting current c_1, so that $\frac{c_1}{c}$ should be constant during the whole time of starting.

The equation for contact 2 is now for the first moment

$$c_1 = \frac{E - E_{b_1}}{R - r_1 + r_a} \quad . \quad . \quad . \quad . \quad (5)$$

In equations (4) and (5) E_{b_1} has the same value; therefore

$$\frac{c_1}{c} = \frac{R + r_a}{R - r_1 + r_a} \quad . \quad . \quad . \quad . \quad (6)$$

On contact 3 the starter has for the first moment still a back E.M.F. E_{b_2}. Corresponding to the normal equation for contact 2,

$$c = \frac{E - E_{b_2}}{R - r_1 + r_a} \quad . \quad . \quad . \quad . \quad (7)$$

Hence we have on contact 3 for the first moment

$$c_1 = \frac{E - E_{b_2}}{R - (r_1 + r_2) + r_a} \quad . \quad . \quad . \quad (8)$$

By dividing equation (8) by (7) we get

$$\frac{c_1}{c} = \frac{R - r_1 + r_a}{R - (r_1 + r_2) + r_a} \quad . \quad . \quad . \quad (9)$$

If, generally, the starter has n steps, then the general equation is as follows :—

$$\frac{c_1}{c} = \frac{R - (r_1 + r_2 + \; . \; . \; . \; + r_{n-1}) + r_a}{R - (r_1 + r_2 + \; . \; . \; . \; + r_{n-1} + r_n) + r_a} \quad (10)$$

With a starter with n steps we have therefore n equations. By multiplying these equations we get

$$\left(\frac{c_1}{c}\right)^n = \frac{R + r_a}{R - (r_1 + r_2 + \; . \; . \; . \; + r_{n-1} + r_n) + r_a} \quad (11)$$

From equation (3) it follows that

$$R = \frac{E}{c_1} - r_a$$

Inserting this value for R in equation (11) we have

$$\left(\frac{c_1}{c}\right)^n = \frac{\frac{E}{c_1} - r_a + r_a}{r_a}$$

for, $R = r_1 + r_2 + \ldots + r_{n-1} + r_n$, or

$$\left(\frac{c_1}{c}\right)^n = \frac{\frac{E}{c_1}}{r_a}.$$

Hence the number of steps is determined by the equation

$$n = \frac{\log\left(\frac{\frac{E}{c_1}}{r_a}\right)}{\log\left(\frac{c_1}{c}\right)} \quad . \; . \; . \; . \; . \; . \quad (12)$$

From equation (12) we learn that the greater the number of steps, the smaller the rush of current from contact to contact. For $c_1 = c$, *i.e.* if there be no alteration of the current, we have

$$n = \frac{\log\left(\frac{\frac{E}{c_1}}{r_a}\right)}{\log 1} = \frac{\log\left(\frac{\frac{E}{c_1}}{r_a}\right)}{0} = \infty$$

Since contact plates for starters are generally manufactured in a certain number of sizes only, having a definite number of steps, the number of steps is frequently given. Therefore we have to determine whether the rush of current c_1 will not be too large with the number of contacts on the starter selected.

From formula (11) it follows that

$$c_1 = c\sqrt[n]{\frac{R + r_a}{R - (r_1 + r_2 + \ldots r_{n-1} + r_n) + r_a}}$$

$$= c\sqrt[n]{\frac{\frac{E}{c_1}}{r_a}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (13)$$

The resistance required for each step may now be determined from equation (6).

From $$\frac{c_1}{c} = \frac{R + r_a}{R - r_1 + r_a}$$

we get $$r_1 = R + r_a - \frac{R + r_a}{1} \cdot \frac{c}{c_1};$$

from equation (9) $$\frac{c_1}{c} = \frac{R - r_1 + r_a}{R - (r_1 + r_2) + r_a}$$

it follows that—

$$r_2 = (R - r_1) + r_a - [(R - r_1) + r_a]\frac{c}{c_1}$$

Generally—

$$r_n = (R - r_1 - r_2 - \ldots - r_{n-1}) + r_a - [(R - r_1 - r_2 - \ldots - r_{n-1}) + r_a] \frac{c}{c_1} \quad (14)$$

Since we have to start with r_1, in calculating the resistance of any step that of the previous step is already known; thus with the step n, the step $(n—1)$ is known.

As will readily be seen from the above formulæ, the resistance of the starter must not be divided into equal steps, thus $r_1 = r_2 = r_3 = \frac{R}{n}$, as then c_1 would not remain constant, but would increase as we move the lever forwards.

The above considerations apply only for electric motors having a constant field, *i.e.* shunt motors; they might, however, also be applied to those series motors which have to exert a constant torque, and which therefore have to work with constant current. This is, for instance, the case with series motors driving double-acting *piston* pumps.

The calculation becomes somewhat more difficult for motors, the current strength of which does not remain constant with varying loads, such as, for instance, fans or exhaust motors, etc. In this case the motor current does not remain constant during the time of starting, but is a function of the speed at any instant. In these cases series motors are generally employed, to which the following considerations apply :—

Curves I, II, and III, Fig. 13, show the speed *n* as a function of the current with different resistances in series with the armature. These curves have been obtained from actual observation of E, *c*, *n*, *e*, on the motor running under normal conditions. The symbols, as in Fig. 12, stand for : E, the total voltage supplied ; *e*, the motor terminal voltage ; *n*, the number of revolutions per minute of the motor ; and *c* for the current.

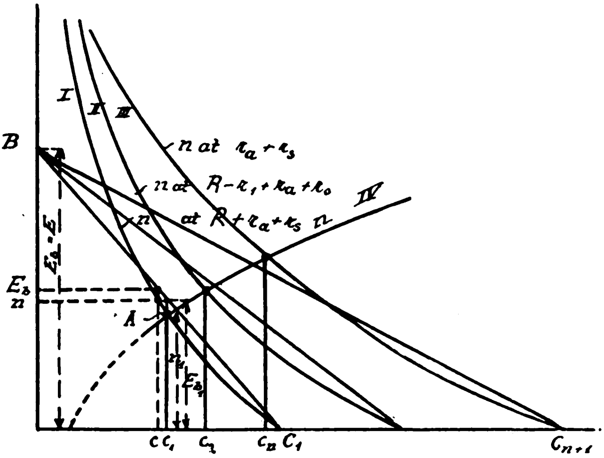

FIG. 13.

From these observations we can draw the curve shown in Fig. 14, for it is

$$E_b = E - c\,(R + r_a + r_s) = e - c\,(r_a + r_s)$$

where R is the resistance in series with the armature, r_a the armature resistance, and r_s the magnet-coil resistance.

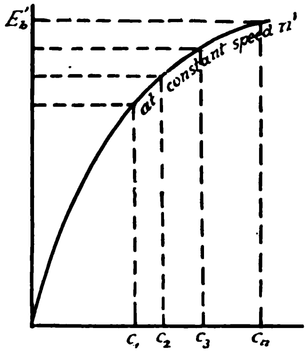

FIG. 14.

[This curve does not represent the open-circuit characteristic, but the curve of the back E.M.F. of the armature, taking into consideration the armature reaction and the voltage-drop due to the current, $c\,(r_a + r_s)$.] If we plot E_b as ordinates in Fig. 13, then the relation between E_b and the current is represented by a straight line. For $c = 0$ we get $E_b = E$, thus point B; for $c = C_1$, $E_b = 0$, because the armature is then stopped, and the total E.M.F., E, is used to produce the current C_1 in the resistance $R + r_a + r_s$. With n resistance steps C_{n+1} would be produced if $R - (r_1 + r_2 + \ldots + r_n) + r_a + r_s$ (*i.e.* the armature resistance and magnet resistance only) were inserted in the circuit. This gives the curve B, C_{n+1}.

In designing the starter we must proceed as follows: Assume a normal current c_n for the motor. The rush of current on the first step must not exceed $c_{\text{max.}}$, hence the total resistance of the starter

$$R = \frac{E}{c_{\text{max.}}} - (r_a + r_s) \quad . \quad . \quad . \quad (15)$$

After the motor has started to run, a back E.M.F., E_{b_1} will be produced, which will depend on speed n and current c (see Fig. 14). To find the voltage E_{b_1} corresponding to this, draw curve I. (Fig. 13). With the arbitrary current c selected, a voltage E_{b_1} is necessary. For a certain current, c, we find from Fig. 14 a certain voltage, E'_b, at a speed n'. The speed corresponding to the current c in Fig. 13 is obtained from the equation

$$\frac{n'}{n} = \frac{E'_b}{E_b}\, ; \; n = n' \, \frac{E_b}{E'_b} \quad . \quad . \quad . \quad (16)$$

By the application of this formula a number of points for curve I may be found. The point of intersection, A, of curves I and IV shows the fall of current $c_{\text{max.}}$ (to c_1) and the speed, n_1, the armature attains with the resistance $R + r_a + r_s$ inserted. The value of c_1 corresponding to E_{b_1} must satisfy the condition

$$E_b = E - c_1 \, (R + r_a + r_s)$$

It can, however, be found directly from the curve B, C_1 in Fig. 13, since this curve is obtained from the above equation.

In moving the lever to contact 2 the current may at first increase again to $c_{\text{max.}}$; then

$$R - r_1 + r_a + r_s = \frac{E - E_{b_1}}{c_{\text{max.}}}$$

$$\text{or } r_1 = R + r_a + r_s - \frac{E - E_{b_1}}{c_{\text{max.}}}$$

We have now in Fig. 13 to draw curve II for the series resistance $R - r_1 + r_a + r_s$. This is done exactly as for curve I. The rest of the calculation will then be clear without further explanation.

In this case the number of steps cannot be determined as simply as before, since the relation between $c_{\text{max.}}$, c_1, c_2 and c is no longer constant. With such starters, however, the number of steps can generally be made much smaller than for motors with a constant value for $\frac{c_{\text{max.}}}{c}$.

For shunt motors similar considerations apply. With these, however, the field is nearly constant; E_b will therefore diverge from the horizontal due to the voltage-drop cr_a caused by the armature current only. Fig. 15 shows the relation between E'_b and c for

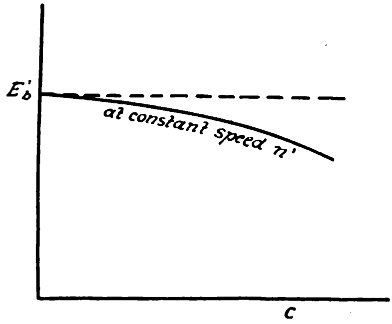

FIG. 15.

a constant exciting current and a constant speed n'. As in Fig. 13, we get for the shunt motor a number of curves, which are shown in Fig. 16. The curves V, VI, VII in Fig. 16 correspond to the curves I, II, and

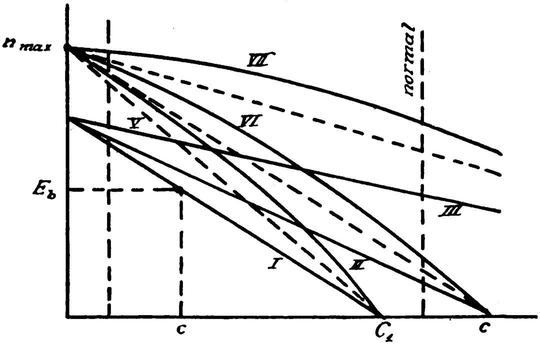

FIG. 16.

III of the series motor in Fig. 13. In the latter case the point of intersection of the curves with the ordinate is at an infinite distance, whereas in the case of a shunt motor the point of intersection with the ordinate is determined by the equation

$$\frac{n}{n'} = \frac{E_b}{E'_b}.$$

For $c = 0, n$ is $= n'$, since then $E_b = E - cr = E - 0$, therefore $E_b = E$. For the rest of the calculation proceed as in the case of the series motor (Formula 15).

Generally the drop of the back E.M.F. in the armature of a shunt motor does not exceed 10 per cent., hence we can well assume it to be constant, and draw curves V, VI, and VII, as straight lines.

The design of a starter for starting a motor without load is somewhat simpler; in this case shunt motors only have to be considered, and we may assume that during the time of starting the curve shown in Fig. 15 is a straight line, for the no-load current of a motor seldom exceeds 15 to 20 per cent. of the normal current, and in any case it is so small that it does not cause a perceptible voltage drop or armature reaction. Such a starter need only have very few steps, since the motor can stand a rush of current which is larger than the working current The rest of the calculation can be made from formulæ (12) and (14) for a constant no-load current c_o.

Large motors, consuming large currents, must not be started without some extra steps which have to be designed so that the current grows gradually to its full strength. It is generally specified that in starting motors the current must not exceed a certain limit, such as, for instance, 50 to 100 per cent. of the working current. This is, in the case of central stations, with the object of preventing the sudden drop of the machine voltage caused by the rush of current.

There are certain cases in which the motors have to start with a larger current than the normal, such as, for instance, traction-motors, etc.; with these particularly the starting current sometimes rises to three times the working current. Such motors are therefore built to stand an overload, and are generally started by means of special controllers. The number of steps is generally very small, about four or five; hence there are considerable rushes of current. The resistance of the single steps are determined by the theory dealt with above.

Fig. 17 shows the starting arrangement for a three-phase motor with a three-phase wound rotor. In order to start the motor, the resistances R are gradually short-circuited until the working position (as shown in figure) is reached, in which position the three-phases are short circuited. Let w_1 be the angular velocity of the rotating field, w_2 that of the rotor. Then generally

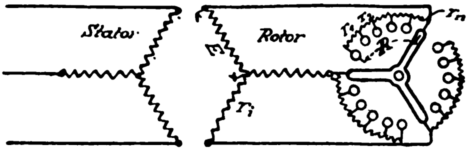

FIG. 17.

$$E = K(w_1 - w_2);$$

where K is a constant comprising the total flux, number of conductors and number of poles;

$$e = \sqrt{3}\, E$$

If the rotor has a low speed, *i.e.* if during the time of starting $w_1 - w_2$ is large, then the periodicity of the current produced in the rotor is large, and with that the self-induction and phase-difference are also large. Fig. 18 shows the well-known voltage diagram: e is the induced E.M.F., e_s is the back E.M.F. of self-induction.

$$e_s = 2\pi f Lc$$

and
$$f = \frac{2p(w_1 - w_2)}{60}$$

where $2p$ is the number of poles. e_a is the effective voltage and f is the frequency. In the diagram the ohmic losses are neglected. To start the rotor a current c_1 must pass through it.

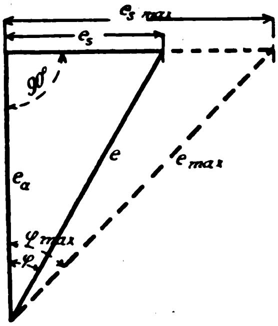

FIG. 18.

When the rotor stops, the lag of phase is a maximum, and we then have

$$c_1 = \frac{e \cos \phi_{\text{max.}}}{2r_i + 2\text{R}} = \frac{\sqrt{3}\text{E} \cos \phi_{\text{max.}}}{2r_i + 2\text{R}}$$

From which

$$\text{R} = \frac{e \cos \phi_{\text{max.}}}{2c_1} - r_i = \frac{e_a}{2c_1} - r_i \quad . \quad (17)$$

In going from contact 1 to contact 2, r_1 is cut out. Let c be normal current on contact 1, then

$$c = \frac{e_{a_1}}{2\text{R} - 2r_i}$$

On touching contact 2 the current will increase to c_1; in the first instant nothing will be altered except the resistance R, which will be R − r_1. The small variation of e_s can be neglected since c_1 differs from c by a few per cent. only ($e_s = 2\pi f \text{L}c$).

Thus
$$c_1 = \frac{e_{a_1}}{2\text{R} - 2r_1 + 2r_i}$$

From which follows (as in the case of continuous current)

$$\frac{c}{c_1} = \frac{2R - 2r_1 + 2r_i}{2R + 2r_i} = \frac{R - r_1 + r_i}{R + r_i}$$

If we determine the ratio $\frac{c}{c_1}$ for each of the succeeding contacts, we get for $n + 1$ contacts or n steps generally

$$\frac{c}{c_1} = \frac{r_i + [R - (r_1 + r_2 + \ldots + r_n)]}{r_i + [R - (r_1 + r_2 + \ldots + r_{n-1})]}$$

Then by multiplying all equations for $\frac{c}{c_1}$ we get—

$$\left(\frac{c}{c_1}\right)^n = \frac{r_i + [R - (r_1 + r_2 + \ldots + r_n)]}{r_i + R} = \frac{r_i}{r_i + R} \quad (18)$$

For the number of steps n we have

$$n = \frac{\log \frac{r_i}{r_i + R}}{\log \left(\frac{c}{c_1}\right)} = \frac{\log \frac{2c_1 r_i}{e_a}}{\log \left(\frac{c}{c_1}\right)} \quad . \quad . \quad (19)$$

Where e_a is the effective voltage when the rotor is still.

$$e_a = e_{\text{max.}} \cos \phi_{\text{max.}}$$
$$e_{\text{max.}} = K(w_1 - w_2)$$

The total number of steps is of course 3 n, and the total number of contacts 3 $(n + 1)$.

The ratio of the rush of current to the normal current becomes

$$\frac{c_1}{c} = \sqrt[n]{\frac{r_i + R}{r_i}}$$

The design of a starter for three-phase motors starting with a variable current is somewhat more complicated. Motors for driving ventilating fans, etc., belong to this class. As with continuous current motors it is best in such cases to couple the motor direct to the machine to be driven, and then find by experiment the curves for calculating the starting resistance.

In Fig. 19 these curves are drawn showing the relation between the current *c*, the voltage e_b on the slip-rings of the rotor, and the revs. per minute *n*. Curve IV shows the relation between the rotor current with short-circuited phases (in this case only the ohmic resistance r_i is in circuit) and the speed of the rotor. By inserting a resistance in the rotor circuit this curve becomes flatter (III and II).

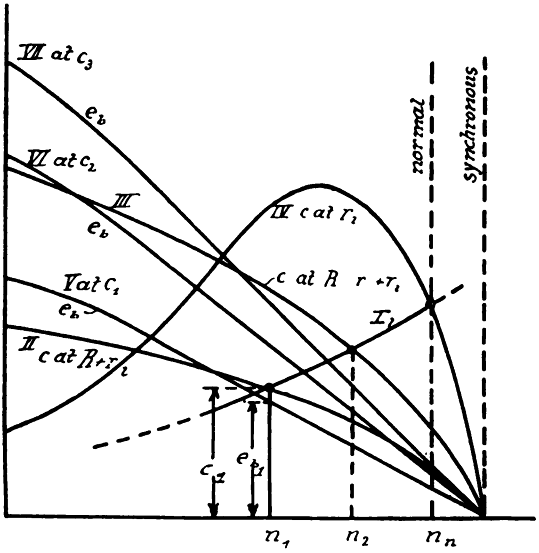

FIG. 19.

Curves V, VI, and VII show the relation between brush voltage and speed with different currents but constant for each curve. Curve I shows the relation between current c and speed n for the normal working of the machine. The curves for brush voltage e_b lie higher for small than for large currents, for e_b is, according to Fig. 18, the resultant of e and $e_s - cr_i$. e should be taken as constant for $n = 0$; as the current increases so $e_s = 2\,\pi f \mathrm{L}c$ increases, hence if c increases e_b decreases. For synchronism e_b must become nil, because then e is also nil $[e = \mathrm{K}(w_1 - w_2)]$. The calculation of the starting resistance is then similar to that for continuous current motors for driving ventilating fans.

The motor may be started with its full working current c, hence—

$$\mathrm{R} = \frac{e_b}{2c} - r_i \quad . \quad . \quad . \quad . \quad (20)$$

where e_b is the brush voltage of the stopping rotor,

$$e_b = e_a - c \times 2r_i = e \cos \phi_{\mathrm{max.}} - c \times 2r_i \quad (21)$$

The armature starts to rotate with increasing speed until it reaches the speed n_1, which is given by the intersection of curves I and II; the current has now fallen to c_1, and the brush voltage is e_{b_1}. On moving to the next contact the effective voltage is at first e_{b_1}, the current may again rise to c; from this the first resistance step r_1 may be determined.

$$c = \frac{e_{b_1}}{2\mathrm{R} - 2r_1 + 2r_i}$$

$$r_1 = \mathrm{R} + r_i - \frac{e_{b_1}}{2c} \quad . \quad . \quad . \quad . \quad (22)$$

The rest of the calculation is then simple. On moving the lever from one contact to the next the current is allowed to rise to its full strength. This starter obviously needs less steps than one for which the ratio of the rush of current to the normal current on each contact has to be kept constant.

CHAPTER IV

MECHANICAL CONSTRUCTION OF STARTERS

THE mechanical details of a starter are: the base-plate to which the contacts and the lever are fixed, and the case for fixing the base-plate and enclosing the resistance material.

Fig. 20 shows one type of contact. For small starters the round contacts are generally employed, since they require only one hole in the base-plate. For fixing these, the connecting wire is driven into a hole in the end of the contact and is soldered, thus keeping the contact in place. Contacts on which sparks are likely to occur—that is, the first contacts of the starter—should be provided with carbons (Fig. 21). It is well to employ a copper strip as sliding contact on the carbon; this should be easily renewable, and so fixed that it makes contact after the main contacts have

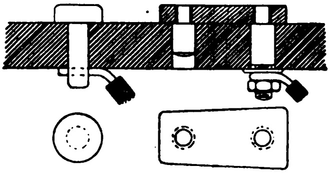

FIG. 20.

been separated. If a spark occurs it will then be between this auxiliary contact and the carbon. The

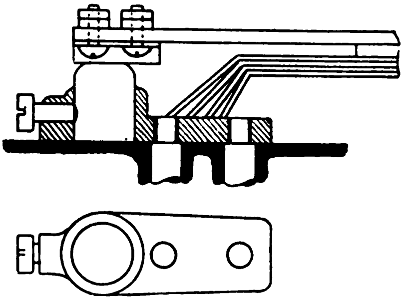

FIG. 21.

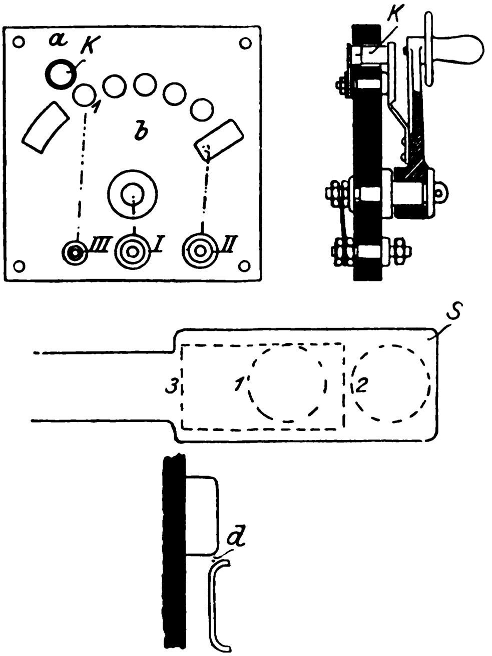

FIG. 22.

edges of the auxiliary contact and the carbon should be rounded, as shown in Chapter II. (Fig. 11), in order to prevent the spark damaging the sliding surface. A similar device is shown in Fig. 22. There the first contact on which sparks are likely to occur in switching off, is connected with a carbon contact K. This latter is fixed in such a position that it makes contact with the sliding spring S after the latter has left contact 1. With these starters, which on account of the contact spring S are not used for more than 20 amperes, an auxiliary spring is not provided. The main spring must therefore be so constructed that the burnt surface does not slide on the contacts.

Fig. 23 serves as an illustration of the base-plate of a

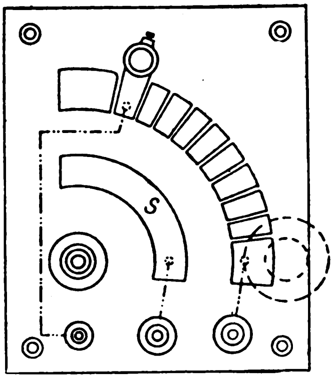

Fig. 23.

larger starter. With such a starter the centre-bolt of the lever must not be used to carry current as in the smaller starter in Fig. 22. For this purpose the quadrant S is provided. The first contact has an auxiliary carbon contact as in Fig. 21.

For large currents **U**-shaped contacts may be used to get the contact surface required. In Fig. 24 a starter is shown, the four contact-fingers F of which are connected together, but insulated from the nut travelling on the spindle S. In this starter the first four contacts are only switching contacts, the motor starts to run only on the last of these. Now, since the current flowing through these contacts is continually increasing,

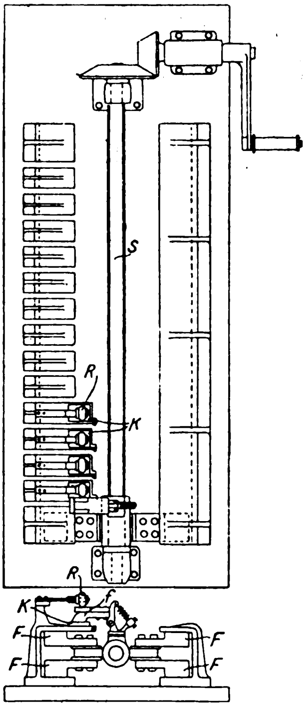

Fig. 24.

an auxiliary means must be provided for making contact before the main spring slides into the first contact. For when the former first touches the latter, the contact surface is too small for the current, and they would at once become red hot. To overcome this difficulty, a copper spring, *f*, is fixed on the upper end of the contact-finger F, so that it is also insulated from the nut. When the spindle S is turned, the nut is moved upwards, and the auxiliary contact *f* is moved under the roller R and pressed on to the carbon K, just when it is directly over the carbon, so that it makes contact with its whole surface. The contact-fingers F are then moved into the contact-pieces, and when there is sufficient contact between them, *f* is pulled up by the spring, and kept in this position until it reaches the next roller.

For large motors, starters are sometimes used in which the single steps are short-circuited by lever switches.

There are many different types of resistance boxes. As material, cast iron or wrought iron is used. Fig. 25 shows a wrought iron construction. The frame of this resistance consists, as will be readily seen from the figure, of strip and angle iron only. Over the rods *b* grooved porcelain insulators are threaded; the resistance wire is then wound over these insulators; the plate carrying the contacts and the lever is then fixed on the top of the box, and the four sides are enclosed with iron stampings. This construction is very suitable in cases where the resistance box and the contacts have to be fixed separately. The contacts are fixed directly on the front of the switchboard, and the resistance behind the switchboard. This construction is also suitable for a resistance box for controllers, which will be described later on.

Fig. 26 shows a cast-iron box K, the sides of which are perforated to secure good ventilation. The resistance coils are drawn through holes in the slate strips L,

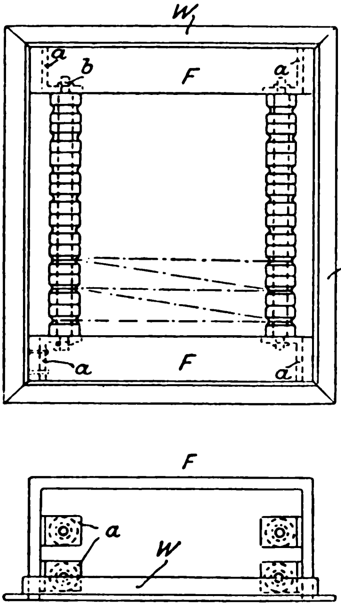

FIG. 25.

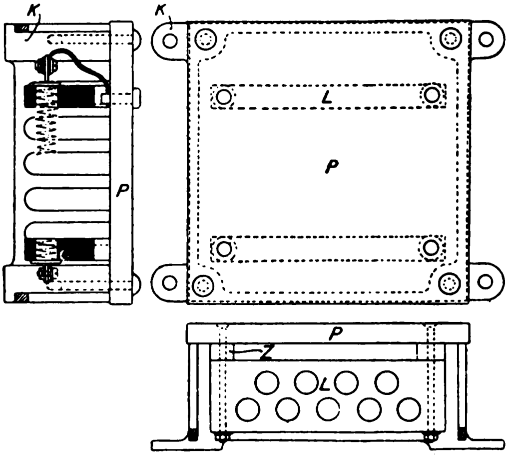

FIG. 26.

and are fixed by simply unwinding the first and last turns. The method of connecting the coils together, and to the contacts, is by clamping their ends together, as shown in Fig. 26. The advantage of this construction, which is used for small starters only, is that the slate strips are fixed directly on to the base P (there must be room between the base and the slate strips to get the connecting wires through the plate—this is effected by the distance pieces Z). The case is fixed on the base after the coils have been fixed in their place, and all the connections have been made. A suitable contact plate for this construction is that shown in Fig. 22.

A method of construction in cast iron for a larger starter is shown in Fig. 27, suitable for motors over 20 B.H.P. The contact plate, which may be constructed as in Fig. 23, is screwed on to a casting, G_1, which is supported by 4 columns, S. These are fixed on another casting, G_2. Two opposite sides of the upper casting G_1

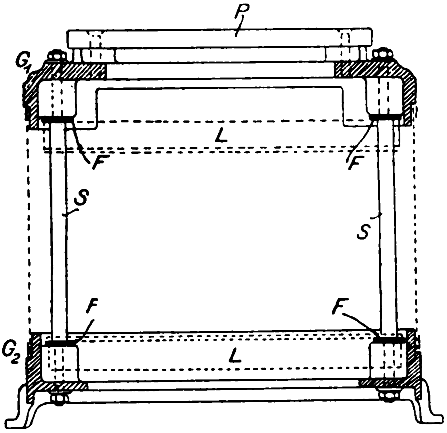

FIG. 27.

are left open to facilitate the making of the connections between contacts and coils. The coils, or for larger currents the resistance strips, are fixed on slate strips L, which are screwed on to iron plates F. The whole frame is enclosed with iron stampings. The method of fixing the coils on such slate strips is shown in Fig. 28. In this figure is also shown the branching of the connections from the contacts; these are fixed with nuts. Soldered joints should always be avoided on starters.

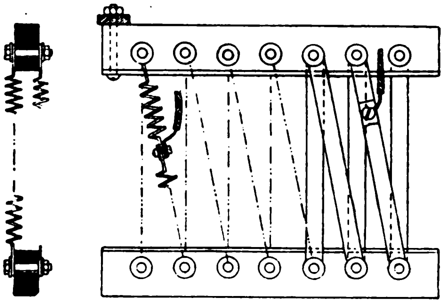
FIG. 28.

The resistance wire is often wound on an earthenware or porcelain cylinder (Fig. 29); these can be fixed on iron rods, which, as in Fig. 25, could be fixed to the two iron strips F; the brackets *a*, the rods *b*, and the porcelain insulators would then be unnecessary.

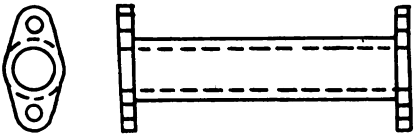
FIG. 29.

Controllers, which are a special type of starters, are employed for motors which have to be frequently started or reversed, also for complicated motor-connections. All controllers must be very strongly built, and must be provided with special devices for reducing or preventing sparking ; also all parts which are likely to be damaged by sparking must be easily renewable. All these details will now be explained separately for each construction.

Fig. 30 shows the construction of a controller in which the contacts are screwed on to a cylinder of insulating material. For these cylinders wood was formerly used, now ambroin is used almost exclusively. The connections are made by turning the cylinder so that the contacts K make contact with the fingers C. The motor and the resistances are connected by means of cables which are fixed in the holes B. Each finger is fixed on a gun-metal clip, G, and is pressed on the contact pieces K by means of the springs F, and insulated from the other fingers and from the square rod S_1. The latter can be insulated by covering it with ebonite or ambroin, the clips are separated from one another by means of square tubes of

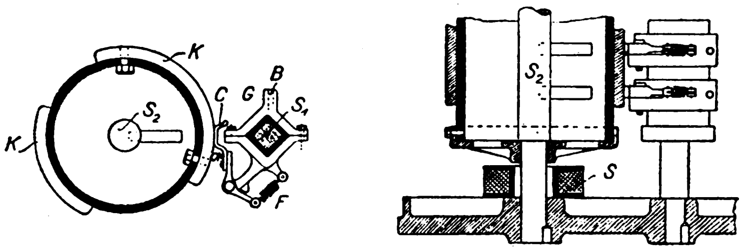

FIG. 30.

insulating material. On the contact finger C an auxiliary contact is screwed, the ends of which are rounded like those of the contact piece K, so that there will be no sparking on the contact surface. The bend of the auxiliary contact must be sufficient to prevent any sparks which may arise at *a* from going further up, to the support of the finger. The magnetic blow-out on this starter consists of an electro-magnet, the coils of which enclose the lower end of the spindle S_2. The latter is made of wrought iron, and also has wrought iron arms, which extend close to the inner surface of the insulating cylinder, and are fixed on a level with the corresponding contact finger. Thus the path of the magnetic lines of force is as follows: From S_2 through the wrought-iron arms, the air at the sparking point, then through S_1, which is also wrought iron, and back through the cast-iron contact plate of the controller. If an arc is formed at the contact finger, it is drawn out by the magnetic field and so broken.

A similar magnetic blow-out may be arranged on a controller, as in Fig. 31. There the electro-magnet coil is slipped over the rib R, the coil itself is oblong. The contact pieces consist of single bronze castings, K, which are fixed on the hexagonal rod S_1; some of these bronze castings are insulated from the others, some are connected together. All the supports for the contact fingers are fixed on an insulating plate, and are prevented from turning round by small pins going through into the insulating plate. The auxiliary contacts B are renewable. The whole controller is provided with a hinged cover. There is also a special door, T, behind the rib for the cables.

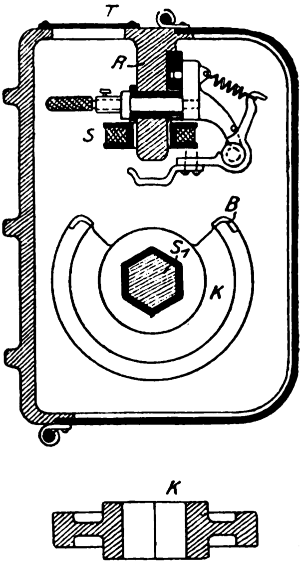

Fig. 31.

A blow-out device which is frequently used in America is shown in Fig. 32. The core K of the coil S is cast on the back of the controller. A cast-iron plate with hinges is fixed on the core by means of two screws, S_1 S_2, and a big casting with rib-shaped extensions F, and which turns on the hinges, is fixed to the core by means of the screw S_3. If there are any repairs to be done on the cylinder or the contact fingers, screw S_3 is taken out, and the casting with the rib-shaped extensions can then be turned on the hinges. With regard to the other details of the starter in Fig 32, it will be noticed from the figure that the cover is fixed by means of screws in order to get the cylinder in from above. The supports for the contact fingers are fixed on an **L**-shaped insulation-piece, which is screwed on the ribs R.

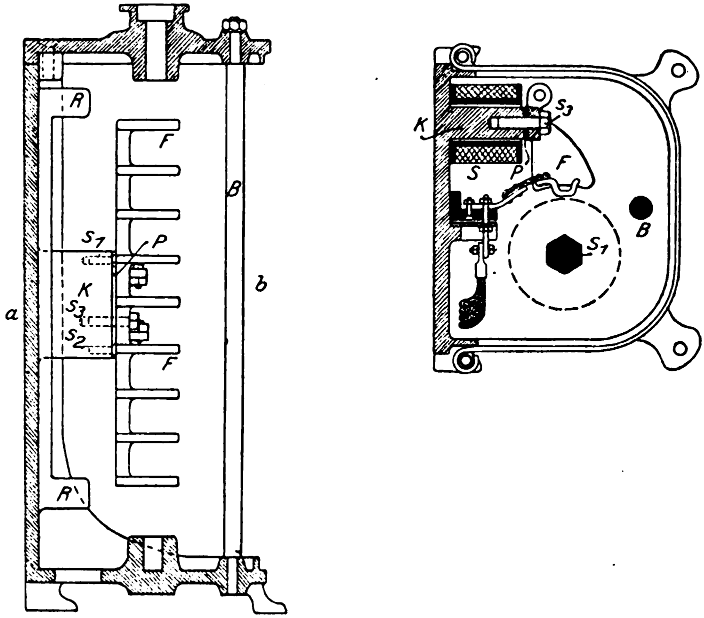

Fig. 32.

The cables are led to a terminal board on which the connections for the cables from the motor and the resistances have to be made. For this purpose some openings are left in the bottom of the controller, as can be seen from Fig. 32.

Controllers, with which there is likely to be severe sparking, are provided with discs of mica or ambroin which project between the fingers, and which prevent the arc from jumping from one finger to the next.

Since the controllers are entirely enclosed, it is necessary to fix a ratchet-wheel on the cylinder axle, to indicate the position of the cylinder. Fig. 33 shows such an arrangement (looking at the cover from below). "Full speed" and "off" have extra deep grooves. The spring which presses the catch against the ratchet-wheel must be strong, so that a certain amount of force is necessary to move the next tooth under the roller of the catch; by this the cylinder is prevented from stopping in any intermediate position.

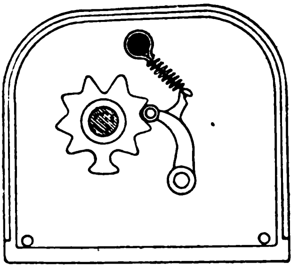

FIG. 33.

Fig. 34 shows an arrangement with which it is only possible to put on or take off the lever when the cylinder is in the "off" position.

During the last few years liquid resistances for starting and regulating motors have come into use both for alternating and continuous current. They are more suitable for alternating than for continuous current, because with alternating current there is no electrolytic decomposition of the liquid. In Fig. 35 a liquid starting resistance is shown. One terminal K_1 is insulated from the cast-iron tank G and connected by means of a flexible cable with the lever, the spindle of which is also insulated from G. From the iron plate M the

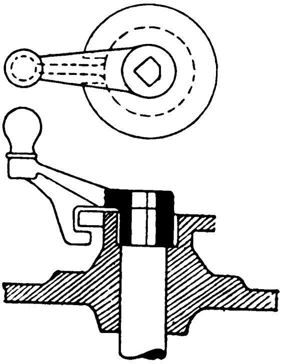

FIG. 34.

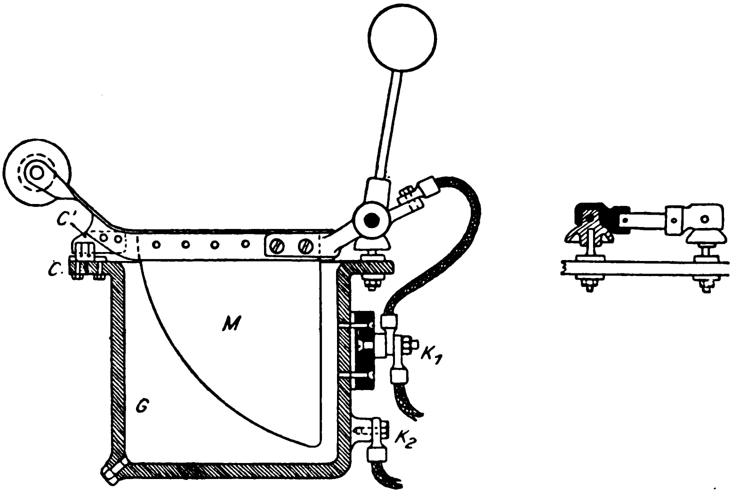

FIG. 35.

current flows through the liquid (sal-ammoniac or soda solution), and from thence to the tank G, to which the terminal K_2 is connected. If the iron plate is slowly lowered into the liquid, the surface immersed in the liquid is gradually increased, and so the resistance is decreased. Finally, the liquid resistance is short-circuited by pressing C_1 into C. To prevent the plate being immersed too quickly there is fixed either an oil dash-pot (Fig. 36) or gearing by means of which the spindle of the lever is turned. From time to time the slime and dirt which is deposited in the tank must be removed. For larger motors several plates may be connected in parallel, or flowing water should be used. For shunt motors a special switch must be provided for the shunt, which must be closed before immersing the plates.

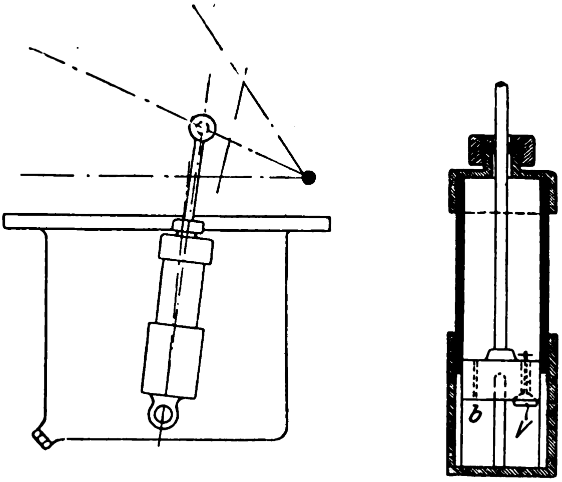

Fig. 36.

Connections of Series Motor Starters.

If in Fig. 37 the auxiliary resistance *r* and the contact *o* be omitted, we have an ordinary starter for a series motor. The auxiliary resistance is provided to protect the insulation of the magnet winding r_s of the motor from damage by the voltage of self-induction, which is produced by suddenly breaking the circuit. The lever contact must be of sufficient width to bridge over the distance between contacts 1 and 0. It is advisable to make $r = r_s$, then *r* must stand half the normal current for a short time. In the off position there is a closed circuit for the induction voltage. Even if this starter is switched off quickly it breaks the circuit almost without a spark.

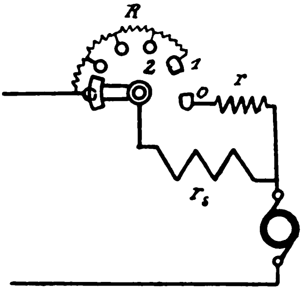

FIG. 37.

The arrangement shown in Fig. 38 is an improvement on that in Fig. 37. The starting lever is provided with a disc *s*, which has a notch at *a*. This disc, by the tension on the spring *f*, prevents an unintentional stoppage of the lever at any contact before the short-circuit contact, which might burn out the resistance material, as it is only designed for a momentary current. When the lever is on the last contact, 2, the magnet *m*, which is in series with the motor, attracts its armature *b* to which the spindle K is fixed, the end of which then enters the notch *a*, thus holding the disc in position. To switch off, the lever of switch A is moved from contact 1 to 3. The distance between 1 and 3 should be made large, and carbon auxiliary contacts should be provided, because the breaking of the circuit cannot be effected without sparking. A must be a quick break switch, the lever of which can stop on contacts 1 or 3, but not between the two. When the main circuit is broken, at the moment switch A is in the intermediate position between 1 and 3, a path is provided for the current produced by the self-induction of the magnet winding r_s, through the solenoid, contact 2, starting resistance R, and back through the auxiliary main c_2. When the magnet *m* releases the disc, lever A has already reached contact 3;

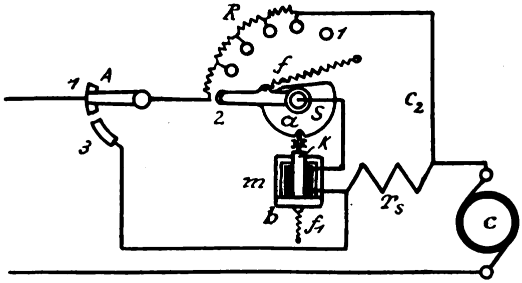

FIG. 38.

a path is then provided for the current of self-induction from r_s through the auxiliary main to contact 3, contact 2, through resistance R and auxiliary main c_2, back to r_s. With this arrangement it is impossible for the starting resistance to be left cut out before the main switch is closed, as spring *f* would pull back the lever, and so the injurious rush of current which would occur if the main switch were closed, with no resistance in the armature circuit, is prevented. When the motor is running, the starting resistance R is in parallel with the magnets r_s, so that a current c_2 is always flowing through it, and there is a loss $= c_2^2R$. It is, however, easily shown that this loss, and also the current, is negligible compared with c_1, so that although the resistance R is in parallel with the magnets, the series motor runs as it would with an ordinary starter.

Take, for instance, the case of a motor running with a current $c = 10$ amps. at 100 volts. Then, allowing 15 amps. for starting, the starting resistance will be $R = \frac{100}{15} = 6{\cdot}67\omega$; assuming a loss of 4 volts in the armature, and 3 in the field magnets, the resistance of the latter will be $\frac{3}{10} = 0{\cdot}3\omega$. The watts lost due to the ohmic resistance is therefore—

$$7 \times 10 = 70 \text{ watts}$$

If we connect up as in Fig. 38, and assume the resistance of the magnet *m* to be $0{\cdot}1\omega$, then we have—

$$c = c_1 + c_2$$
$$c_2 = c - c_1,$$

then $$c_1 = \frac{\mathrm{R}}{m + r_s} \cdot \quad c_2 = \frac{\mathrm{R}}{m + r}(c - c_1)$$

therefore—

$$c_1 = \frac{c\mathrm{R}}{m + r_s\left(1 + \frac{\mathrm{R}}{m + r_s}\right)} = \frac{10 \times 6{\cdot}67}{0{\cdot}1 + 0{\cdot}3\left(1 + \frac{6{\cdot}67}{0{\cdot}1 + 0{\cdot}3}\right)} = 9{\cdot}44 \text{ amps}$$

Hence the exciting current will be 9·44 amps instead of 10 amps. With low saturation the motor will therefore run a little faster; with high saturation there will be no perceptible difference of speed. The total watts lost due to ohmic resistance will now be—

$$c^2 \times 0{\cdot}4 + c_1^2(r_s + m) + c_2^2\mathrm{R} = \text{about } 76 \text{ watts}$$

against 70 watts with the ordinary connections. With large motors the difference will be smaller still.

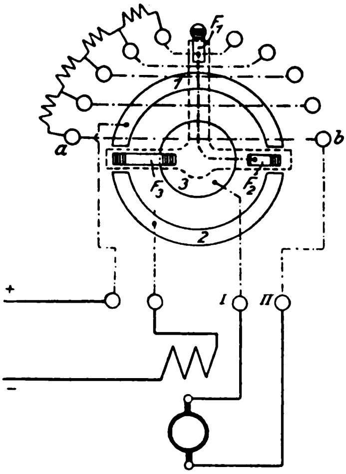

Fig. 39.

In Fig. 39 a reversing switch is shown. For reversing the direction of rotation of a continuous current motor, either the field or the armature current must be reversed. The latter is the better method, since there is less self-induction in the armature than in the field. In the diagram given for a reversing switch for a series motor the current in the armature is reversed. If the lever with the spring F_1 is on the contact *a*, then the path of the current is from positive supply to contact bar 1, spring F_2, spring F_1, *a*, *b*, armature terminal II, through armature to I, bar 3, spring F_3, bar 2, through field to negative of supply. On tracing the path of the current when the lever is in its extreme position to the right, *i.e.* covering the contact *b*, we find that the direction of the armature current has been reversed, but the direction of the current in the field remains the same as before; thus, positive supply to bar 1, spring F_3, bar 3, to armature terminal I, through armature, II, *b*, spring F_1, spring F_2, bar 2, through field to negative of supply.

The three springs F_1, F_2, and F_3 are insulated from the lever; F_1 and F_2 are connected together; they may be left uninsulated from the lever, so that the lever forms the connection between them, but in any case F_3 must be insulated from the lever.

Before leaving the subject of series motor starters, a description of two controllers for reversing series motors shall be given. Fig. 40 shows the arrangement of the contacts on a cylinder of insulating material, which could be constructed as shown in Fig. 30. The cylinder is shown cut through in the off position and laid out. I, II, III, etc., represent the fixed contact fingers. On turning the cylinder until line 1 is under the contact fingers, the path of the current is as follows: positive of supply, field F, blow-out B, VII, VI, armature, V, I, r_1, r_2, r_3 to negative.

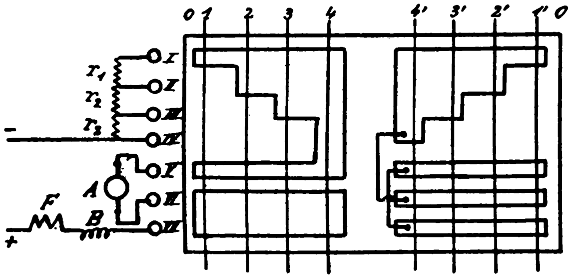

FIG. 40.

In position 2, the first step r_1 of the starting resistance is short-circuited, in position 3, r_1 and r_2, and in position 4, r_1, r_2, and r_3 are short-circuited. It is impossible to go further than 4, as the shape of the locking-wheel (see Fig. 33) does not allow of any further motion in this direction. To reverse the motor, the lever has first to be turned back to the "off" position, and afterwards to 1', 2', 3', 4'. On tracing the path of the current, it will be found that it flows through the armature in the opposite direction; as the direction of the current in the field remains the same as before, the motor will run in the opposite direction.

Fig. 41 shows a more recent construction (see also Fig. 31), which, although requiring more contacts, is still cheaper to manufacture than the construction shown in Fig. 30. All contact-pieces are connected together, but there is an insulating disc between VI and VII, shown in Fig. 41 by a thick line. Turning the cylinder to position 1, the current flows from + supply through field F, magnetic blow-out B, IX, VII, armature, V, I, r_1, r_2, r_3, back to negative. On position 1' the armature current is reversed. The difference in length between the two constructions is only small, in spite of the larger number of contacts in the latter, since with this construction mica discs can be placed between the contacts, so that the distance between the latter can be kept small, without there being any danger of sparking across. The diameter of the cylinder can always be made smaller with the construction shown in Fig. 31 than with that shown in Fig. 30.

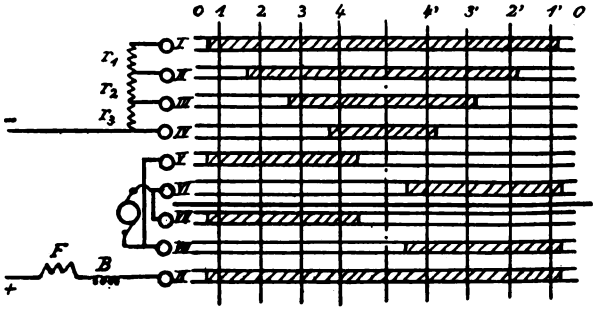

FIG. 41.

Other types of controllers will be dealt with in the last chapter.

Connections of Shunt Motor Starters.

Starters for shunt motors are nowadays almost invariably provided with a sparkless break as first suggested by Fischer-Hinnen. This connection is shown in Fig. 42. One end of the shunt-winding is connected with the first resistance contact. The explanation is as follows: When the motor is running at its normal speed, the lever of the starter is on contact 2, the starting resistance is then in series with the magnet winding; this resistance, however, is scarcely 10 per cent. of the shunt resistance; the magnetizing current is, therefore, only weakened a very little. Since now with high flux density, which is usual with modern machines, the total flux does not decrease in proportion to the current, but slower, there will be no perceptible increase of speed from this weakening of the field. When the motor is to be switched off, the lever must be turned quickly in a clockwise direction. In coming off contact 1, the main circuit is broken, but by this quick break of the main circuit

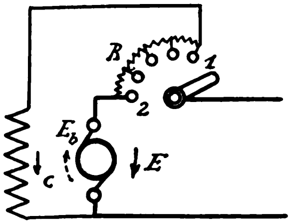

FIG. 42.

no break or reversal of the magnetizing current takes place, for the total E.M.F. of the armature E_b is now switched on to the magnet winding, and E_b is nearly exactly equal to E (viz. $E_b = E - cr_a$), so that no extra current is produced by the self-induction of the magnet winding. As may be seen from this explanation, firstly the motor must be running at full speed, and secondly, it must be switched off very quickly. This can also be seen by an example. Let the motor be taking 30 amps. at 110 volts, and let the starting resistance be $2{\cdot}75w$. We will assume a voltage-drop of 5 in the armature, then the back E.M.F. of the motor will be $110 - 5 = 105$ volts at full speed. Let the magnetizing current be 3 per cent. of the armature current, then $\frac{30}{100} \times 3 = 0{\cdot}9$ amps. The resistance of the magnet winding $R_{sh} = \frac{110}{0{\cdot}9} = 122{\cdot}2\omega$. With the starting resistance in series the magnetizing current will be $c_{sh} = \dfrac{110}{122{\cdot}2 + 2{\cdot}75} = 0{\cdot}882$ amps. If the starter be switched off quickly, the speed of the armature does not alter during the time of switching off, hence its back E.M.F. is 105 volts for the first moment, and at the moment of switching off the magnetizing current $c_{sh} = \dfrac{105}{122{\cdot}2 + 2{\cdot}75} = 0{\cdot}842$ amps. Now, the field will not decrease so rapidly as the magnetizing current, so that hardly any extra current is produced by self-induction. The machine is now working as a generator on its own field, and this latter decreases as the speed of the armature decreases.

In Fig. 42 the centre bolt of the lever is used as a current lead. The terminals of the starter in Fig. 22 are also connected with the contacts by this method of connection; the main is thus connected with I, the armature with II, and the magnet winding with III. For larger currents, the main is led to a contact-bar, S (see Fig. 23).

A quick break can be effected in starters having connections, as in Fig. 42, by a spring *f* (see Fig. 43).

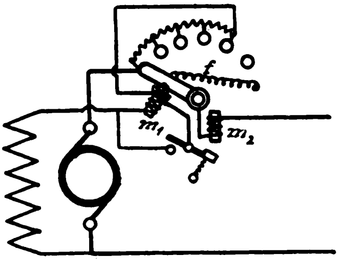

FIG. 43.

m_1 is an electro-magnet, which is connected in series with the magnet winding, keeping the lever on the short-circuit contact as long as sufficient current is flowing through the field-magnets. To switch off the motor, a simple quick-break switch is inserted in one of the mains. Then, as shown above, the back E.M.F. of the armature acts on the field, and the magnet m_1 through which the magnetizing current is passing holds the lever until the current becomes too weak; then the spring *f* draws the lever quickly to the off contact.

The magnet m_1 protects the motor against too large an armature current and too high a speed, which might be caused by a break in the shunt-winding; for if there is no magnetizing current, spring *f* draws the lever back to its off position; also the lever cannot stop at any but the short-circuit contact, so that the starter is protected against a current flowing through it continuously, and so burning out the coils. The magnet m_2 acts as an overload release. If the current becomes too excessive, owing to an overload, then magnet m_2 attracts its keeper, which short-circuits m_1, so that the latter releases the lever.

In Figs. 44 and 45 types of magnets are shown such as are used for the magnets mentioned in the starter, Fig. 43 (m_1 or m_2). The one shown in Fig. 45 is the better type. It consists of a small steel casting almost entirely closed, into the bottom of which a wrought-iron core is screwed, which holds the coil in. In Fig. 46 a keeper is shown suitable for this

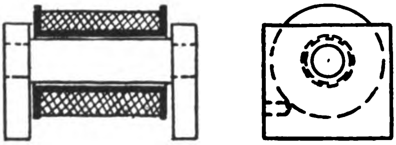

FIG. 44.

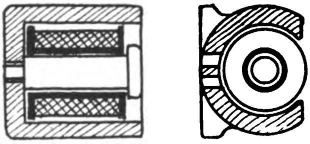

FIG. 45.

magnet. The keeper should not actually touch the iron of the magnet, because it is then liable to stick there; this can be prevented by very thin brass discs or by

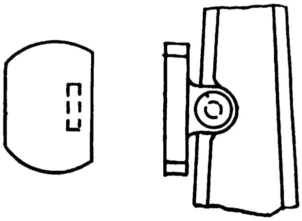

FIG. 46.

a small brass pin, which is screwed into the end of the magnet.

For reversing shunt motors the same applies as for reversing series motors: either reversal of the field or armature current. The latter method is also the better for shunt motors. A diagram of connections for a reversing switch is shown in Fig. 47. With the lever to the left, and therefore F_1 on *a*, the path of the current is as follows:—

$$+,\ \text{I, bar 1}\left\{\begin{array}{l}\text{Spring } F_4\text{, spring } F_1, a, b, \text{ V, armature,}\\ \quad\text{IV, bar 3, spring } F_3\text{, bar 2, II,}\\ \text{Spring } F_2\text{, bar 4, III, field}\end{array}\right\}-$$

hence at bar 1 the current branches.

When the lever is on contact *b*, the direction of the armature current is reversed, but that of the field remains the same. Thus—

$$+,\ \text{I, bar 1}\left\{\begin{array}{l}\text{Spring } F_3\text{, bar 3, IV, armature, V, } b,\\ \quad\text{spring } F_1\text{, spring } F_4\text{, bar 2, II,}\\ \text{Spring } F_2\text{, bar 4, III, field.}\end{array}\right\}-$$

The connection for sparkless break shown in Fig. 42

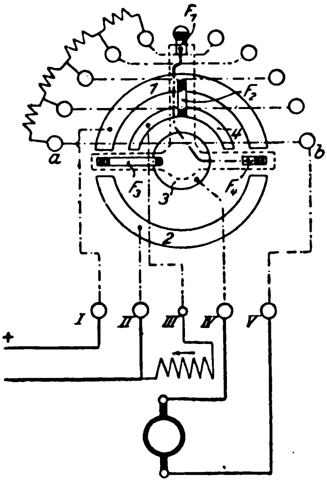

FIG. 47.

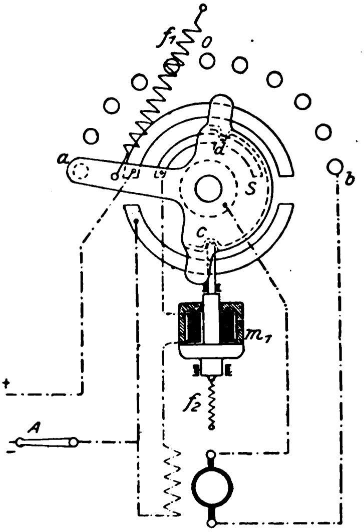

FIG. 48.

is also applied to reversing switches (see Fig. 48). The lever is fitted with a disc, S, which has notches at *c* and *d*. If the switch A is closed, then the magnet m_1, which is connected in series with the shunt-winding, is magnetized, and so attracts its armature, so that the pin forming the upper end of the armature holds the lever in position at *a*. The lever is prevented from stopping at any contact between *a* and *o* or *b* and *o* by the spring f_1. The motor is switched off by means of the switch A. After the circuit is broken, the lever remains for some little time at *a*, because the magnet m_1 is still magnetized by the armature. When finally the magnetizing current becomes too weak, then spring f_2 draws back the armature of the magnet m_1, and the lever is pulled back to *o* by the spring f_1. The same takes place on contact *b*. The other part of this switch is similar to the one shown in Fig. 47.

Connections for Three-phase Motor Starters

The usual starting position of a three-phase motor with a three-phase wound armature is shown in Fig. 17. The starting resistance in this diagram consists of three parts. To avoid the large number of contacts and resistance coils, Niethammer has devised an arrangement which is shown in Fig. 49. The four brushes, 1, 2, 3, 4, sliding on the slip-rings of the rotor, are connected to the terminals *a*, *b*, and *c* of the starter. In starting (with the lever in the position shown), the three-phases are switched in series with each other, and in series with the starting resistance R; the three currents differing from each other in phase by 120° have

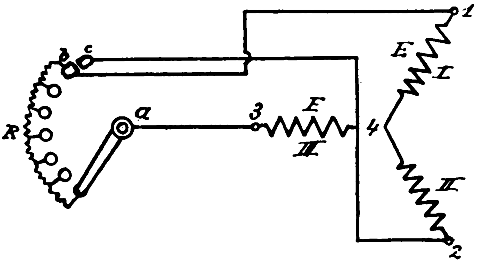

FIG. 49.

a voltage of 2 E. With the usual method of connection as in Fig. 17, $3\ \mathrm{R} = 3\frac{\mathrm{E}}{c}$; with this method of connection $2\ \mathrm{R} = \frac{2\mathrm{E}}{c}$. On turning the lever to the contacts *b* and *c*, which are covered simultaneously, phases I and II are connected in series and short-circuited; phase III is short-circuited on itself. Let *r* be the ohmic resistance of one phase, *e* the voltage of the rotor when running at full load, then the current in the short-circuited phase III, $c_1 = \frac{e}{r}$. The current in the other two phases, I and II, will be $c_2 = c_3 = \frac{1{\cdot}73e}{2r}$. Hence the current in phases I and II is about 13 per cent. smaller than that in phase III. The motor works nearly as well with this connection as with the usual one. At the same outputs the ratio of slip is in the two cases as follows:—

$$3c_1^2r : c_1^2r + c_2^2r\left(\frac{\sqrt{3}}{2}\right)^2 = 1{\cdot}2 : 1$$

To reverse the direction of rotation of three-phase motors, two phases of either the rotor or stator must be changed. In Fig. 50 a reversing switch for a three-phase motor is shown, with which phases II and III can be changed. The lever consists of four arms, on one of which the changing arrangement is fixed. In Fig. 50 the switch is shown in the "off" position. On turning the arms to a, a_1, a_2, the rotor is short-circuited, also on b, b_1, b_2. On a, a_1, a_2, phase II of the stator is connected with main III, and phase III with main II; on b, b_1, b_2, phase II is connected with main II, and phase III with main III. The large number of contacts with these reversing switches can be avoided by applying Niethammer's arrangement.

Finally, some methods of starting may be mentioned suitable for small motors. Fig. 51 represents a curve showing the relation between torque T and slip σ. From this curve we see that below the maximum torque there are always two values of the slip σ for the same torque. This fact is made use of for starting small three-phase motors. Well-designed motors should always work far below the maximum shown in the diagram, so that they do not tend to come out of step if overloaded. Hence for starting small motors we must work on that part of the torque curve which ascends with decreasing slip and increasing speed. Since the curve ascends with decreasing slip, and the motor has always to exert a greater torque in starting than it has in working, it will start well, but with a far greater current than the normal, and therefore also with a

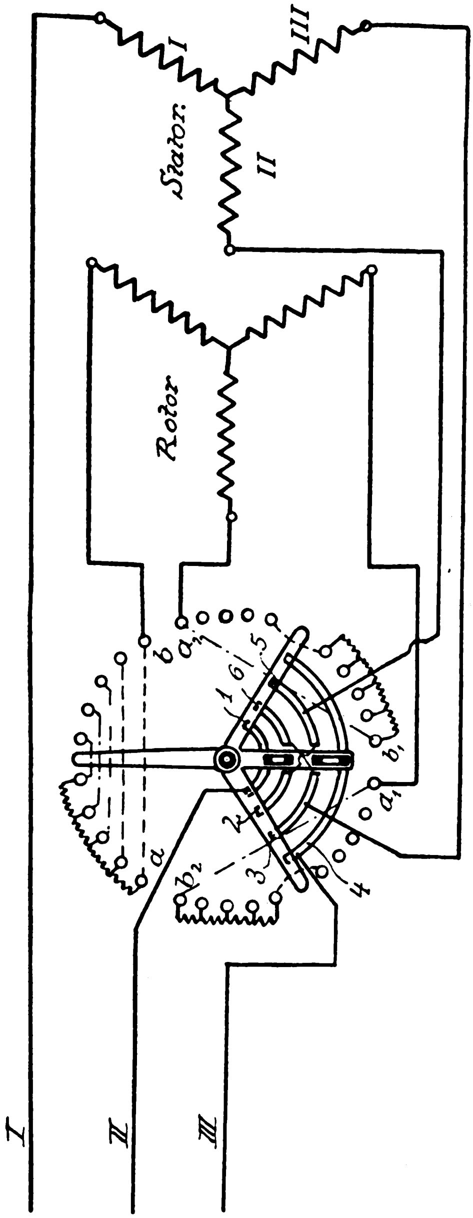

FIG. 50.

smaller resistance. Owing to the large starting current this method cannot well be used for motors over 5 B.H.P.

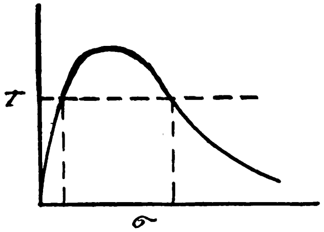

Fig. 51.

Motors with a smaller output than 5 B.H.P. can very well be started in this way.

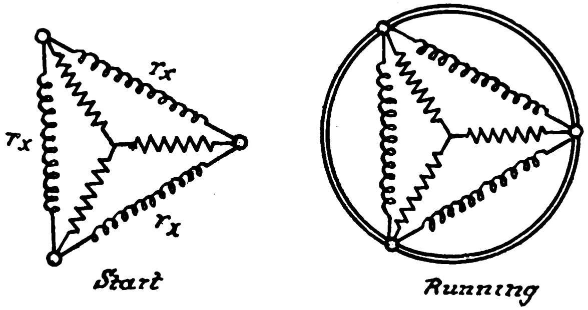

Fig. 52.

In Fig. 52 the connections for such a motor are shown. While starting, the ends of the three-phases are connected by three resistances, r_x. To avoid the use of slip-rings, the resistances are connected direct to the ends of the rotor windings. When the motor has been started, the three ends of the phases are short-circuited, in parallel with the rotating resistances r_x.

The mechanical construction of such a short-circuiting device is shown in Fig. 53. By turning the lever to the right, ring A, and ring B which is connected with A by a ball-bearing, are moved to the left. The three ends of the phases are led to the springs C, which are insulated from each other. On sliding ring B over the three springs, they are connected together and the

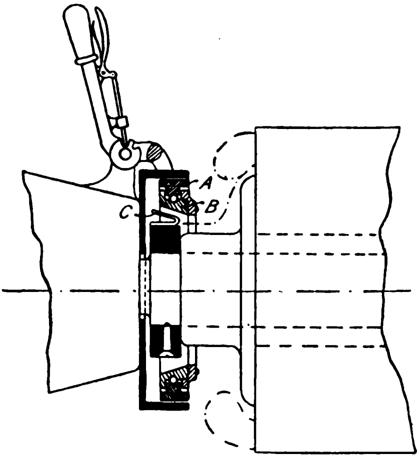

Fig. 53.

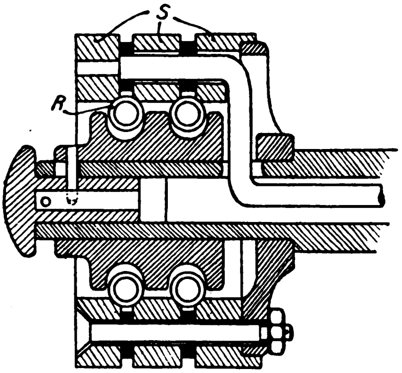

Fig. 54.

resistances are short-circuited. After the resistances are short-circuited, ring B rotates with C whilst A is fixed: hence the two rings must be connected by a ball-bearing. In Fig. 54 a short-circuiting device is shown, as manufactured by Brown, Boveri & Co. The three slip-rings, S, are short-circuited by wire spirals, R, which are pressed between the rings S by the button on the shaft end.

In Fig. 55 a method of starting (Patent Görges, Siemens & Halske) is shown. While starting, the short-circuit connections between the phases (indicated by dotted lines) are broken. The winding of the rotor consists of two parts, one of which is wound with twice as many turns as the other, and which is therefore twice the resistance. Hence the ratio of the E.M.F.'s of the two windings is $\frac{2e}{e}$. While starting the windings act against each other, so that the effective E.M.F. is only $2e - e = e$. By short-circuiting the phases (dotted circle) the windings are connected in parallel. The

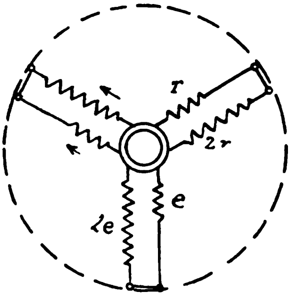

FIG. 55.

voltage drop in the two windings in each phase is the same; in the larger winding $c = \frac{2e}{2r} = \frac{e}{r}$, and in the smaller $c = \frac{e}{r}$. Both in the larger and smaller winding the voltage $e = cr$ is lost.

Motors of three horse-power and under may be started by switching on the primary current (in the field) gradually. The motor will not start in this case under load. In Fig. 56 the connections for starting by this method are shown. The terminals of the starter are in this case connected to the star points of the stator. The motor has a simple squirrel-cage rotor.

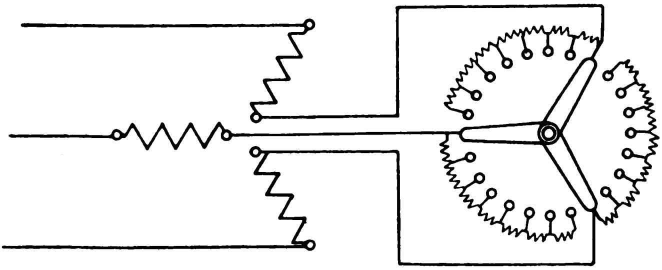

FIG. 56.

Connections for Single-phase Motor Starters

Single-phase motors can be started either by turning their rotors by some mechanical means or by the production of an artificial rotating field. The field in the latter case must be provided with an auxiliary winding, which acts at right angles to the main field. The diagram of connections is as shown in Fig. 57. During the time of starting the two-way switch is in the position indicated. To produce a rotating field there must be a difference of phase between the currents flowing through the two windings; this phase difference can be produced, for instance, by putting a choking coil in series with the auxiliary winding. As it is not possible to produce a phase difference of 90° between these two currents, the rotating field will be very unsteady, but will be sufficient for starting the motor without much load. When the motor has got up to speed, the auxiliary winding and the choking coil are cut out by switching the two-way switch to the position shown dotted. The auxiliary winding and choking coil can be of smaller dimensions than the main winding, as they are only used for a short time.

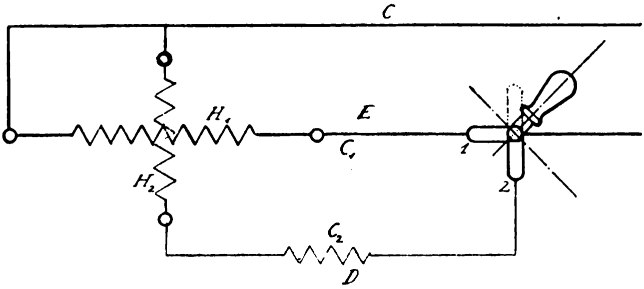

Fig. 57.

In Fig. 58, C represents the total current (see also Fig. 57), C_1 the current in the main winding (the difference of phase between C_1 and voltage E is only small), and C_2 the current in the auxiliary winding H_2, which differs in phase from the main current by the angle ϕ. Since now C_2 decreases as the angle ϕ increases, the choking coil (see Fig. 59) is made adjustable—

$$C_2 = \frac{E}{\text{apparent resistance}}$$

The apparent resistance $= \sqrt{r^2 + L^2p^2}$, where r is the ohmic resistance, L the coefficient of self-induction

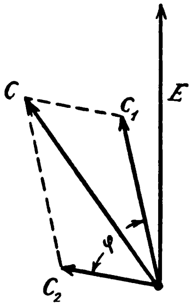

FIG. 58.

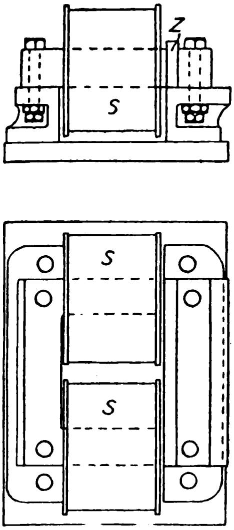

FIG. 59.

$= \frac{\phi}{C}$, ϕ is the total flux produced by the current C, and $p = 2\pi f$, where f is the periodicity per second of the alternating current. The coefficient of self-induction of the coil can be varied by inserting some insulating discs, Z, in the air-gap. After determining by experiment the most suitable length of air-gap for starting the motor, the coil is fixed. The insulating discs, Z, then prevent any alteration in the air-gap.

As in all alternating-current apparatus all nuts on this choking coil must be locked by means of split pins, to prevent their being loosened by the vibration of all iron parts.

Automatic-starting Appliances

Automatic starters are often employed for motors driving pumps which supply water for a hydraulic plant or to fill a tank. In these cases the motor has to be started automatically when the water falls below a certain level, and has to be stopped when the tank or hydraulic cylinder is filled. Automatic starters are also employed with advantage for starting lifts, hoists, etc.

The following methods of actuating automatic starters must be considered: gravity, centrifugal governors and small auxiliary motors, and with alternating-current choking coils.

A very ingenious device for starting a motor has been patented by Siemens and Halske. The method will be clear from Fig. 60. The advantage of this method is that the starting of the motor is made to depend on the increasing speed of the motor. The latter drives a centrifugal governor by means of a cord pulley ;

as the speed of the motor increases, the balls of the governor open out and turn the lever H on the shaft *a*; on this shaft *a* a disc, S, is fixed. When this disc is turned, the carbon contact 1′ makes contact with the carbon contact 1. The leads are connected with the last fixed contact and the disc S respectively, and from the diagram it will be seen that when contact is made between 1′ and 1 the whole resistance is inserted in the circuit. The movable contacts are fixed on springs on the disc, so that on moving the disc further contact is made between 2′ and 2, thus short-circuiting the first part of the resistance. The more the balls of the governor open out, the more carbons make contact. When the motor reaches its normal speed, all the carbons make contact, and so all the resistance is short-circuited. To use this arrangement for the supply of water to a tank, all that is needed is a float working a switch in the main circuit. The arrangement just

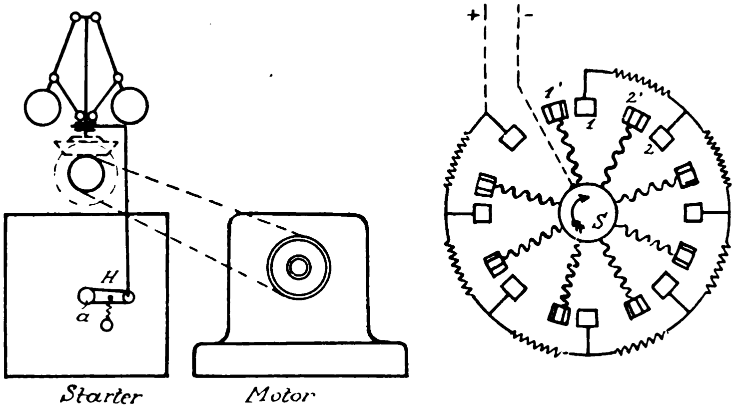

FIG. 60.

described is used also for elevators. A change-over switch can then be worked by the controlling rope of the elevator, to reverse the armature current for reversing the direction of rotation of the motor.

Another device is shown diagrammatically in Fig. 61. A solenoid, S, is connected across the brushes of the motor. When the armature is stationary, the spring *s* holds the starting lever on contact 1. When the circuit is closed with a switch, the armature starts to rotate. The more voltage the armature produces by its own rotation, the more current will flow through the solenoid S. The iron core is then attracted, and the starting resistance gradually short-circuited. This

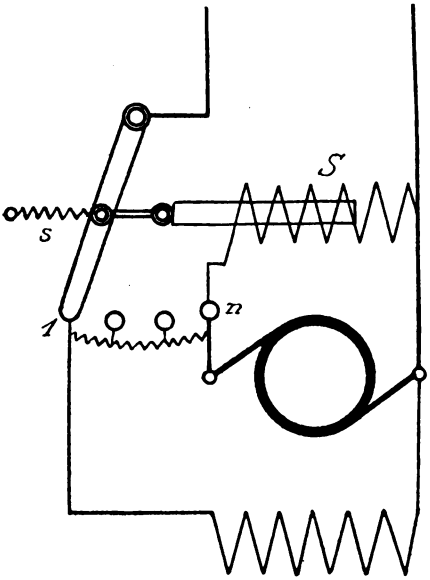

Fig. 61.

arrangement is also entirely dependent on the increase of speed of the armature.

The automatic starters shown in Figs. 62 and 63 do not depend on the increase of the speed of the armature. Fig. 63 represents the more recent type.

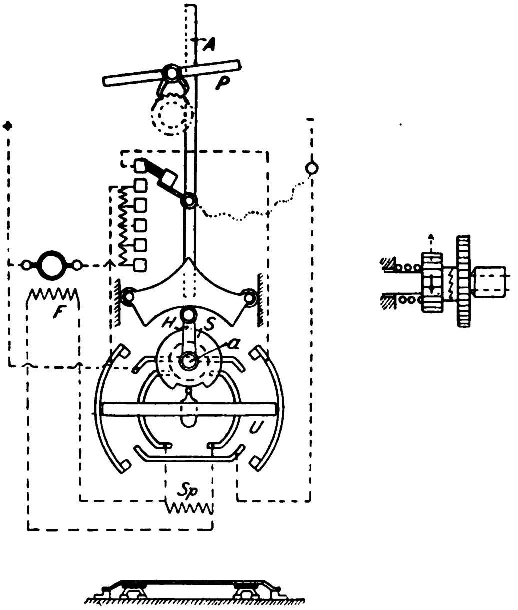

FIG. 62.

The change-over switch, U (Fig. 62), is worked by means of the disc S, which is actuated by turning the cord-pulley on spindle *a* (this is done from the lift). At the same time lever H is turned through 90°; rack A is thus released, and sinks downwards, the rate of lowering being regulated by the escapement and pendulum P. On switching off, lever H returns to its upright position, lifting rack A again; while the rack is being raised, the escapement and pendulum are released. The change over switch also returns to its original position. To reverse the direction of rotation of the motor with this arrangement the field current is reversed. A safety resistance, Sp, is put in parallel with the field to prevent damage due to the self-induction voltage.

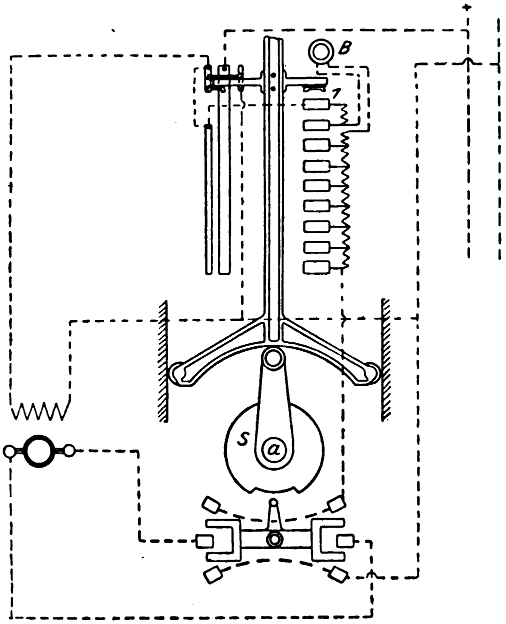

Fig. 63.

In the more recent design (see Fig. 63) the armature current is reversed to reverse the direction of rotation. The spark caused on contact 1 by switching off, is extinguished by the magnetic blow-out B ; the latter is only switched in at the moment when it is required. On switching off, the magnet winding is short-circuited ;

this position is indicated in the figure. The short-circuiting of the magnet-winding must of course be effected without previously breaking the shunt current. The mechanical design of this starter is similar to the one described previously.

Finally, an automatic arrangement for starting induction motors may be mentioned (Patent Krížík Fischer-Hinnen). Three choking-coils, S, are connected in parallel with 3 ohmic resistances, r (see Fig. 64).

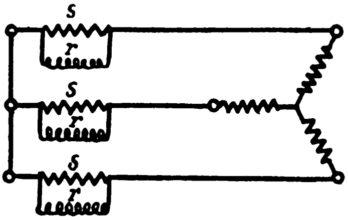

FIG. 64.

When the rotor is stationary, the periodicity of the current induced by the rotating field, and hence the apparent resistance of the three choking-coils, will be large. As the speed of the rotor increases, the periodicity of its currents *decreases,* till finally the resistances r are nearly short-circuited by the choking-coils S, the ohmic resistance of which is but small. According to Fischer-Hinnen, the best effect for starting is reached when $r = p\mathrm{L}$, where L = coefficient of self-induction of a choking-coil.

Very large starters are worked by small auxiliary motors; the latter are then started automatically. For this purpose a starter like the one shown in Fig. 24

would be suitable. The small motor drives the spindle, and is automatically switched off as soon as the spring contacts of the starter are in their highest position. To switch off, the motor has to be reversed. When breaking the circuit, the main starter must be short-circuited ; this is done by a switch, which is closed when the spring contacts reach their highest position, and is opened again when the auxiliary motor has brought the spring contacts to their lowest position. The switching on or off of the small motor can be done by means of a float, whilst it has to automatically switch itself off by throwing over a lever.

CHAPTER V

CALCULATION OF REGULATING RESISTANCES FOR GENERATORS AND MOTORS

Generators

In the case of generators, regulating resistances are used for varying the voltage; in the case of motors, for varying the speed. The case of regulators for generators will be dealt with first.

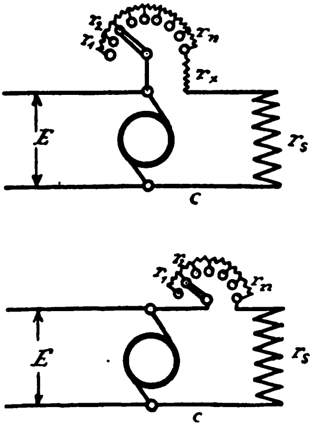

FIG. 65.

The two diagrams of connections in Fig. 65 will serve to explain the symbols used. We will assume that the voltage E required to produce the current *c* in the shunt winding of a continuous-current generator is constant. This is the simpler case and the one usually met with in practice.

In Fig. 66, curve I represents the open circuit

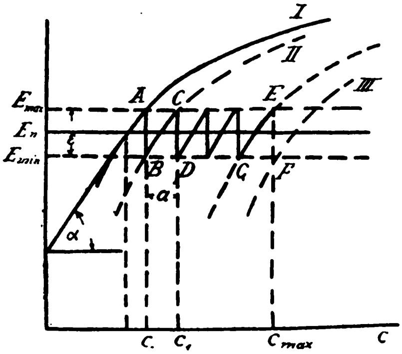

FIG. 66.

characteristic of a shunt dynamo. Let the normal voltage be E_n, allowing a variation of voltage from $E_{max.}$ to $E_{min.}$ (with constant bus-bar voltage, $E_{min.}$ must equal this bus-bar voltage, if the machine is to supply the normal current). On switching on, the voltage of the machine is $E_{max.}$ Curve II shows the displacement of the voltage-curve due to armature reaction and the ohmic voltage-drop in the armature. The horizontal difference between curves I and II is constant $= a$, for curve II represents a definite constant current in the armature, hence the reacting ampere-turns and the voltage-drop are constant throughout the curve. The pressure variation allowed (from $E_{max.}$ to $E_{min.}$) being very small (generally about 4 per cent.), the brush position will not be altered. Assuming that the machine is running without load, and has a voltage of $E_{max.}$ then on loading the machine its terminal voltage will fall; the maximum permissible voltage-drop being ϵ, the voltage will fall to $E_{min.}$, *i.e.* from A to B, the exciting current being constant $= c_0$. If the load is increased beyond the current corresponding to the dynamic characteristic II, we must increase the magnetizing current by short-circuiting part of the shunt resistance, in order to prevent a further drop of the terminal voltage of the generator. We must therefore increase the shunt current to c_1, when the terminal voltage will rise to point C corresponding to E_{max}. On further increasing the load, the terminal voltage will come down to D ($E_{min.}$), and so on; till finally at F the maximum load will be reached, with the minimum terminal voltage allowed.

The number of steps of the shunt regulator is hence equal to the number of alterations of the shunt current c required, hence equal to the number of small rectangles ABCD, which make up the large rectangle ABFE. The area of the large rectangle ABFE is $\epsilon \times (c_{max.} - c_0)$. Both $c_{max.}$ and c_0 may be found by a simple experiment. The area of the small rectangle ABCD is equal to $\epsilon \times a$, where $a = \frac{\epsilon}{\tan \alpha}$, and where α is the angle which the tangent to the point A on the no-load characteristic makes with the abscissa.

To determine the number of steps and the values of the single resistances r_1, r_2, r_3, etc., the following experiments must be made: (1) The open circuit, or no-load characteristic with decreasing exciting current; (2) the exciting current $c_{\text{max.}}$ at maximum load. Then

$$n = \frac{\epsilon(c_{\text{max.}} - c_o)}{\epsilon . \dfrac{\epsilon}{\tan \alpha}} = \frac{(c_{\text{max.}} - c_o) \tan \alpha}{\epsilon} \quad . \quad (23)$$

where, of course, ϵ and $c_{\text{max.}} - c_o$ must be drawn to the same scale; if c is in inches, then ϵ must also be in inches.

We proceed in the same way to find α.

Let the shunt resistance be r_s, (see Fig. 65); then we have the following equations: the total resistance

$$R = r_1 + r_2 + r_3 + \ . \ . \ . \ + r_n = \frac{E}{c_o} - r_s \quad (24)$$

For the first step of the regulator we have

$$R - r_1 = \frac{E}{c_1} - r_s$$

And since

$$c_1 = c_o + a = c_o + \frac{\epsilon}{\tan \alpha}$$

$$r_1 = R + r_s - \frac{E}{c_o + a}$$

$$r_2 = R + r_s - \frac{E}{c_o + 2a} - r_1$$

$$r_n = R + r_s - \frac{E}{c_o + na} - (r_1 + r_2 + r_3 + \ . \ . \ . \ + r_{n-1}) \quad (25)$$

In Fig. 65 a resistance r_x is inserted in the shunt circuit, which cannot be cut out; this resistance, of course, must be added to r_s in the above formulæ.

In the following are given some general rules for designing shunt regulators.

Any prime mover runs slower when loaded than without load. If, as in Fig. 67, curve I gives the no-load characteristic, and II the characteristic with load (both for the same speed n), then the curves III and IV for any higher speed can be found from the equation

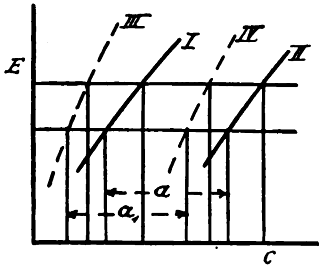

FIG. 67.

$$E_n : E_{n1} = n : n_1$$

The horizontal distance between the curves I and II is, of course, the same as between III and IV, since in both cases the back ampere turns are equal, hence $a = a_1$. It will therefore always be safe to take the no-load characteristic curve with maximum speed of the machine.

To determine the total resistance of the regulator the resistance of the magnets must be taken cold, whereas for determining the size of a permanent resistance, as r_x, the resistance of the magnets when hot must be taken into account, so that the machine can still give its maximum output, even if after some time the magnets get hot. Further, as mentioned above, the open circuit characteristic should be taken with decreasing magnetizing current.

Another case is that of a self-excited shunt dynamo; the exciting voltage is then no longer constant, but decreases as the load increases.

In Fig. 68 is a curve showing the drop of voltage as the load increases. This curve, which within practical limits can be considered a straight line makes an angle α with the horizontal; this angle can be used for determining the subdivision of the resistance. Hence a curve must be taken from the machine, showing the relation between main current C and voltage E, with self-excitation and constant shunt resistance, and another curve must be taken with constant voltage E_n, showing the relation between shunt current and main current.

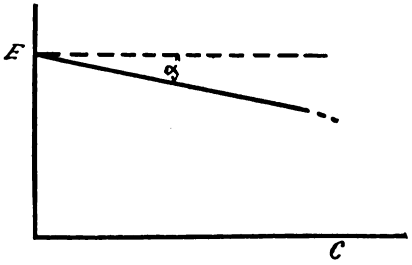

FIG. 68.

Fig. 69 gives all the data required for the calculation. Assuming the machine to be running light, with all the regulating resistance in the shunt circuit. Let its voltage then be $E_{max.}$ at a point A. When the machine is loaded, its voltage will decrease, until, with main current C_1, it falls to $E_{min.}$ (point B). After cutting out the first step of the regulating resistance, the voltage again rises to $E_{max.}$ (point C). The number of steps, n, now becomes equal to the number of

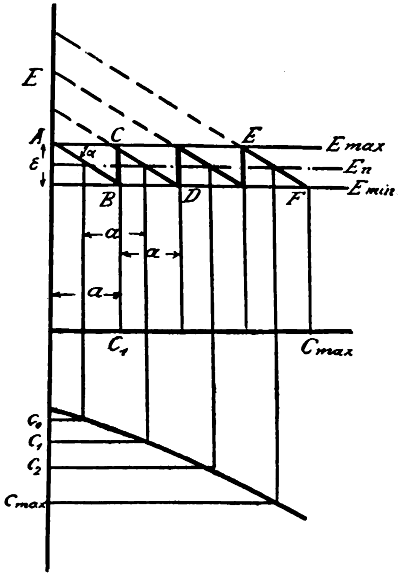

FIG. 69.

parallelograms, ABDC, into which the parallelogram ABFE can be divided.

$$n = \frac{\epsilon\,(C_{max.} - C_1)}{\epsilon a}$$

where $a = \dfrac{\epsilon}{\tan\,\alpha}$ and $\epsilon = E_{max.} - E_{min.}$

Further, $C_1 = a = \dfrac{\epsilon}{\tan\,\alpha}$

so that—

$$n = \frac{\epsilon\left(C_{max.} - \dfrac{\epsilon}{\tan\,\alpha}\right)\tan\,\alpha}{\epsilon^2} = \frac{C_{max.}\tan\,\alpha - \epsilon}{\epsilon} \quad . \quad (26)$$

where $C_{max.}$ and ϵ should be drawn to the same scale. Whilst the voltage decreases from A to B, the shunt resistance is constant, so that

$$R + r_s = r_1 + r_2 + \ldots + r_n + r_s = \frac{E_n}{c_1}$$

where c_1 is obtained from the load curve (C as a function of the magnetizing current c), and c_1 corresponds to a current $\frac{a}{2}$.

The first step of resistance is then

$$(R + r_s) - r_1 = \frac{E_n}{c_2}$$

$$r_1 = \frac{E_n}{c_1} - \frac{E_n}{c_2}$$

$$r_2 = \frac{E_n}{c_2} - \frac{E_n}{c_3}$$

Generally—

$$r_n = \frac{E_n}{c_n} - \frac{E_n}{c_{n+1}} \quad . \quad . \quad (27)$$

The magnetizing currents c_1, c_2 . . . correspond to loads which differ from each other by $a = \frac{\epsilon}{\tan \alpha}$; c_1 corresponds to a load $C = \frac{a}{2}$, c_2 to $\frac{a}{2} + a$, c_3 to $\frac{a}{2} + 2a$, etc., c_n to $\frac{a}{2} + (n - 1)a$.

To calculate the resistance r_x to be switched permanently in series with the magnets, and in considering the speed variation between full and no load, the same rules must be applied as above.

In some cases it is not possible to obtain an external characteristic of the machine in the test-room. In such cases the open circuit characteristic for normal speed will be found sufficient (curve I, Fig. 70), and the angle α may be found by running the machine with a speed much lower than normal, but fully exciting the magnets. If the armature be then loaded, and the drop of voltage observed for increasing load, the angle α can be found from the experiment. This method is only exact for big machines having small armature reaction. It follows from Fig. 70 that the number of steps, n, is found in exactly the same way as before.

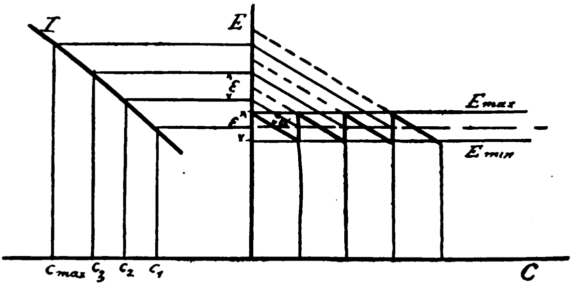

FIG. 70.

$$n = \frac{C_{\text{max.}} \tan \alpha - \epsilon}{\epsilon}$$

The total resistance now becomes

$$R + r_s = \frac{E_{\text{min.}} + \frac{\epsilon}{2}}{c_1} = \frac{E_n}{c_1} \quad . \quad . \quad (28)$$

It follows that the first step is

$$R + r_s - r_1 = \frac{E_n}{c_2}$$

$$r_1 = R + r_s - \frac{E_n}{c_2} = \frac{E_n}{c_1} - \frac{E_n}{c_2}$$

$$r_2 = \frac{E_n}{c_2} - \frac{E_n}{c_3}$$

$$r_n = \frac{E_n}{c_n} - \frac{E_n}{c_{n+1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

where the exciting currents c_1, c_2, c_3, etc., correspond to the following points on the open circuit characteristic :—

c_1 to E_n, c_2 to $E_n + \epsilon$, c_3 to $E_n + 2\epsilon$

generally c_n to $E_n + (n - 1)\epsilon$

If the voltage curve (see Fig. 68) is not straight, the angle α is determined by drawing a tangent to $C_{max.}$ We then get a larger angle, and since $n = \frac{C_{max.} \tan \alpha - \epsilon}{\epsilon}$, the number of steps becomes somewhat too large. The regulation of the exciting current then becomes on the first few steps finer than is necessary. To avoid obtaining too many steps with a curve which drops rapidly (see Fig. 71), tangents should be drawn at several points. Let in Fig. 71

n_1 be the number of steps between C = O and C = C_1
n_2 ,, ,, ,, C_1 and C_2
n_3 ,, ,, ,, C_2 ,, $C_{max.}$

then the total number of steps will be

$$n = n_1 + n_2 + n_3 = \frac{C_1 \tan \alpha_1 - \epsilon}{\epsilon} + \frac{(C_2 - C_1) \tan \alpha_2 - \epsilon}{\epsilon} + \frac{(C_{\text{max.}} - C_2) \tan \alpha_3 - \epsilon}{\epsilon} \quad . \; . \quad (30)$$

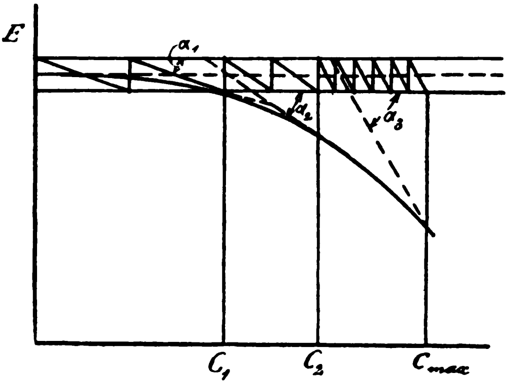

FIG. 71.

The first steps of each group then still regulate a little too fine, and only the last steps regulate between $E_{\text{max.}}$ and $E_{\text{min.}}$

The voltage of series dynamos can, as in Fig. 72, be

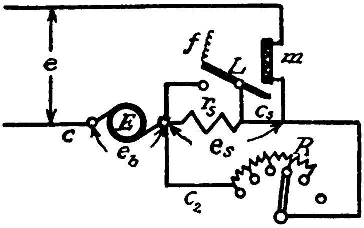

FIG. 72.

regulated by putting a resistance R in parallel with the magnet winding r_s.

Series motors are sometimes employed for power transmission, and then one generator feeds one motor; the voltage of the former does not then need regulating at all. If the generator runs at a constant speed the motor will also run at a constant speed. Sometimes, however, it is desirable to regulate the voltage of a series dynamo—if, for instance, the generator supplies a motor working a pump. If the quantity of water to be pumped is to be regulated, the voltage applied to the motor must be varied.

In Fig. 73 curve I shows the relation between the E.M.F., E of the machine, and the main current c, provided that the current in the series winding $c_s = c$, *i.e.* if the lever of the regulating resistance R is on the off contact. The armature reaction may be found by drawing a curve showing the relation between the armature voltage e_b and current c (III). The difference between the ordinates of curves I and III represents the drop of volts; if we also draw the straight line cr_a,

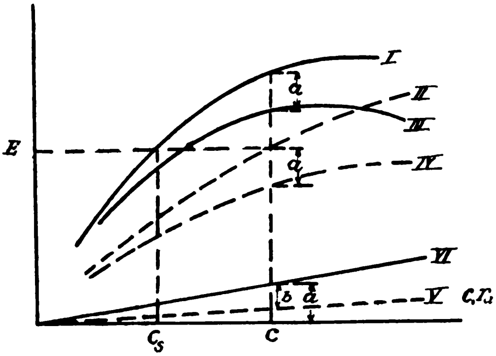

FIG. 73.

where r_a is the armature resistance, (V), then, if curve VI represents the difference between curves I and III, b represents the armature reaction.

With a regulating resistance R (Fig. 72), in parallel with the magnets, the combined resistance of regulator and magnets will be

$$\frac{1}{\frac{1}{r_s}+\frac{1}{R}}=\frac{r_sR}{R+r_s}$$

In the combined resistance there is a voltage drop e_s—

$$e_s=c\frac{r_sR}{r_s+R}$$

Since with a constant resistance, R, this voltage is directly proportional to the load c, the magnetizing current

$$c_s=\frac{e_s}{r_s}=\frac{c\frac{r_sR}{r_s+R}}{r_s}$$

must also be directly proportional to the load c. A new curve (II) may therefore easily be drawn to represent the relation between the E.M.F., E and the load. The voltage corresponding to the magnetizing current c_s can be drawn on the ordinate, which corresponds to c; from this ordinate, a must be subtracted for the armature reaction and voltage drop in the armature, and we get curve IV, representing the voltage on the brushes e_b. The terminal voltage

$$e=E-(cr_a+c_sr_s)$$

In compound dynamos shunt regulators are used either for switching in parallel or for altering the load before switching on the machine. Also a few steps must be provided to compensate for the difference in voltage caused by the heating of the winding.

Fig. 74 shows the connections for a compound machine with long shunt, *i.e.* with shunt coils connected across the armature and the series coils. We then have

$$c = \frac{e_k}{r_s + \mathrm{R}}$$

$$e_k = \mathrm{E} - [(c + \mathrm{C})(r_a + r_{ser})]$$

At starting r_a, r_{ser}, and r_s are somewhat lower than after the machine has been running for some time, so that e_k, and therefore c, will be a little greater; if it is essential for the terminal voltage to be absolutely constant, a regulating resistance R would be required; the effect of this difference in resistance is never very great. The regulator R is generally used for switching the machine on or off the mains. To switch one machine in parallel with one or several others, the voltage of the machine to be switched in must be made equal to the bus-bar

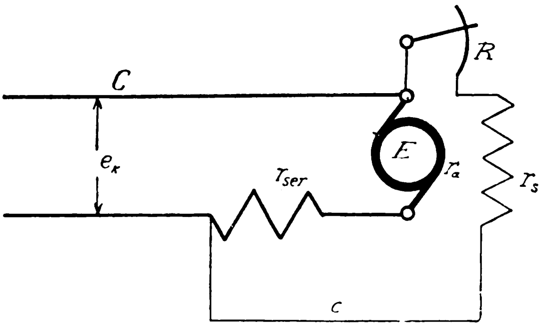

FIG. 74.

voltage; then the main switch must be closed and the E.M.F. of the machine gradually increased by cutting out some of the regulating resistance, till the machine takes up its full share of the load. To switch the machine off the mains, the switch must not be opened while the machine is loaded, but the voltage of the machine must be lowered by inserting resistance in the shunt circuit until it is taking no load; the switch may then be opened.

The same applies to a compound dynamo with short shunt, as in Fig. 75. The shunt is in this case connected directly across the brushes, hence the magnetizing current will be

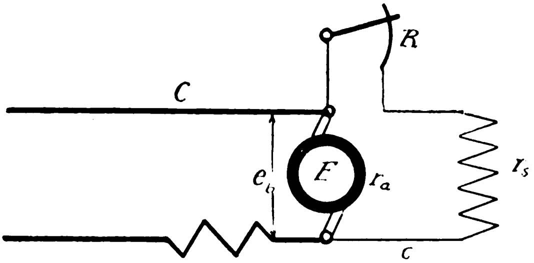

FIG. 75.

$$c = \frac{e_b}{r_s + R} \text{ and } e_b = E - (c + C)r_a$$

In designing regulators for alternators, the same method can be used as for continuous current machines. Fig. 76 shows a scheme, in which several generators, G, are running in parallel. The exciting currents c are taken from the bus-bars E, the voltage of which is produced by the continuous current dynamos M. The calculation of the regulating resistances for these exciting dynamos is made by the method described at the beginning of this chapter (see Figs. 65 and 66).

In the calculation of the regulating resistances R of the alternators we use the second method (see Figs. 68 and 69); the angle α must then be determined at several points, since the voltage drop with an inductive load ($\cos \phi = 0{\cdot}8$ is the most usual case) is not represented by a straight line, but by a convex curve curving upwards; therefore we must proceed as in Fig. 71.

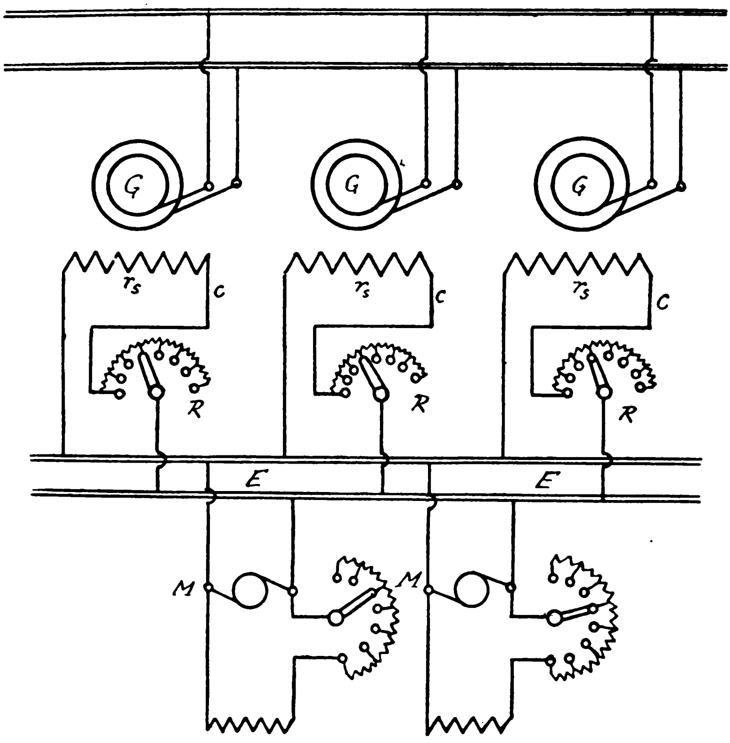

FIG. 76.

The arrangement given in Fig. 76 for exciting the alternator has the disadvantage that there is a greater loss of energy for excitation than in that shown in Fig. 77. In the latter case each alternator has its own exciter; the voltage of the alternator is regulated by

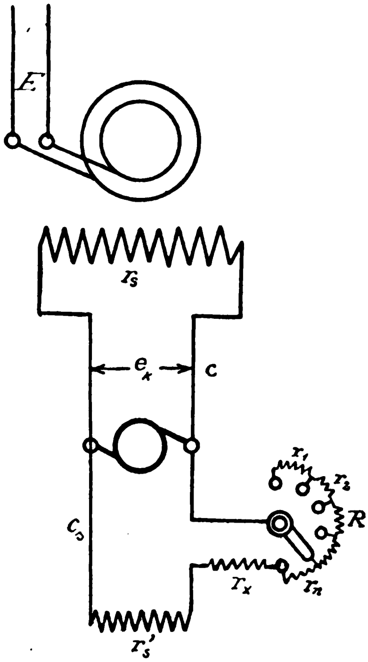

Fig. 77.

means of the shunt regulator of the exciter. The arrangement shown in Fig. 77 has the disadvantage, however, that the alternator voltage cannot follow the regulation as quickly as in Fig. 76, for, with only one regulator in the shunt circuit of the continuous current generator, the self-induction of the windings r'_s and

r_s opposes any alteration in the current strength. The arrangement shown in Fig. 77 is not used so often as that shown in Fig. 76. However, for determining the regulating resistance R (Fig. 77), the curves shown in Fig. 78 can be used. Curve I shows the drop of the terminal voltage E of the alternator, with inductive load. Curve II shows the relation between the exciting current c and the load C. The determination of the number of steps must be made by the method described for Figs. 68 and 69. The exciting current c for any load C can be found from curve II. The former represents the load on

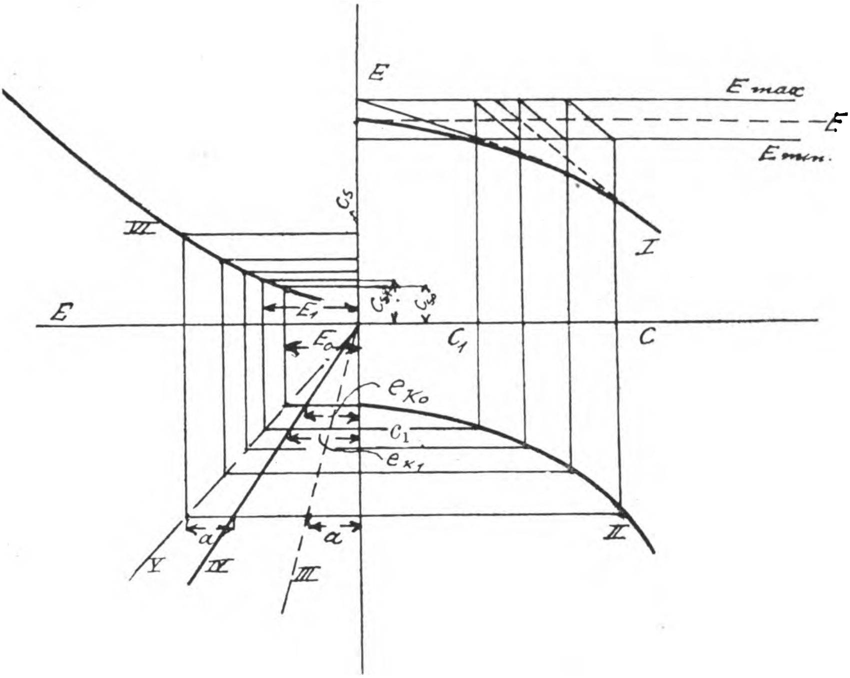

FIG. 78.

the exciter. Curve IV is a straight line ($e_k = cr_s$), and shows the terminal voltage e_k of the exciter required for a certain excitation. Curve III gives the armature reaction and voltage drop in the exciter armature. Adding the ordinates a of curve III to curve IV, we get in curve V the E.M.F. to be induced in the exciter armature, the exciting current c_s of which follows from the open circuit characteristic (curve VI) of the exciter.

The exciting current c_1, for instance, corresponds to the load C_1, and $e_{k_1} = c_1 r_s$ also corresponds to C_1. $E_1 = e_{k_1}$ + armature reaction + $r_a(c_s + c)$; then the first step of the regulating resistance will be

$$r_1 = \frac{E_0}{c_{s_0}} - \frac{E_1}{c_{s_1}}, \text{ etc.},$$

but the real exciting current—

$$c'_s = \frac{e_k}{r'_s + R}$$

Motors

Regulating resistances of motors are used for varying the speed. The speed regulation may be effected in two different ways: below the normal speed by inserting resistance in the armature circuit, or above the normal speed by weakening the field.

With speed regulation below the normal the motor is working with varying voltage. Hence the output is smallest at the lowest speed, for the output is equal to the input minus the losses. With regard to the work done by the motor, there are two possible cases; either the work done by the motor decreases in direct proportion to the speed, or it is an exponential function of the speed.

If, for instance, the motor is driving a pump, then the work varies as the speed, and the torque on the pulley remains constant. The work done is equal to the torque multiplied by the angular velocity of the armature. The latter depends on the speed of the motor, hence, if the torque is constant the work done is directly proportional to the speed.

Since, to regulate the speed below the normal, the voltage is altered by inserting resistance in the armature circuit, the current must remain constant if the opposing torque and the field remain constant, for the torque of the armature varies as the product of the current and the field strength.

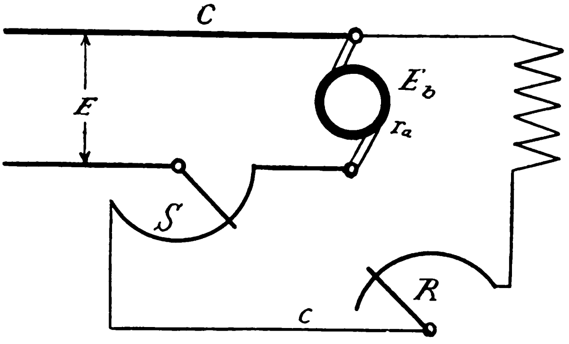

FIG. 79.

In shunt motors with a constant supply voltage E (see Fig. 79), the field is constant, provided that the lever of the shunt regulating resistance R is not moved.

At normal speed both the regulating resistance R and the starter A are short circuited. Let E_b be the back E.M.F. of the armature, and r_a its resistance. Then the speed—

$$n = \frac{E_b \times 60 \times 10^8 \times p_1}{\phi D p} \quad . \quad . \quad . \quad . \quad . \quad (31)$$

where ϕ = total flux per pole;
D = number of conductors on armature;
p_1 = number of armature sections in parallel;
p = number of poles

$$E_b = E - \{(C - c)(r_a + S)\} \quad . \quad . \quad (32)$$

From these two equations the size of the series resistance S can be calculated.

This resistance can also be determined from measurements on the motor at full load and normal speed. For this purpose E, C, r_a, c, n must be measured; then $E_b = E - (C - c)r_a$ with the starter short-circuited. If the speed has to be regulated from n down to n', then a back E.M.F. E_b' is required, the value of which is—

$$E_b' = \frac{n' E_b}{n}$$

$$E_b' = E - \{(C - c)(r_a + S)\}$$

where S is that part of the starting-resistance which must be designed to stand a permanent load.

In designing regulating resistances suitable for reducing the speed of motors, driving-fans, etc., the method described for the design of starters in Chapter III. should be used. From curve IV (Fig. 13) the current c required for a given speed n of a series motor may be found. From Fig. 14 the voltage E_b' is found corresponding to this c with constant speed n'. Hence, the voltage E_b required at a speed n—

$$E_b = E_b' \frac{n}{n'}$$

Let r_s be the magnet resistance of the series motor; then (Fig. 12)—

$$E_b = E - c(r_a + r_s + R)$$

$$R = \frac{E - c(r_a + r_s) - E_b' \frac{n}{n'}}{c}$$

For three-phase motors all the necessary data can be obtained from Fig. 19 and the theory developed in Chapter III.

This method of speed regulation always causes a loss of energy in the regulator. If the working current is C, and the resistance inserted is R, then the loss in the regulator is C^2R. This method is only applicable to small motors, because, firstly, the loss of energy would be too great with large motors; and, secondly, on account of the space required by, and the large cost of, such large resistances, as have to be built for permanent load.

We shall now deal with the regulation of speed above the normal. Firstly, for shunt motors according to formula (31),

$$n = \frac{E_b \cdot 60 \cdot 10^8 p_1}{\phi D p}$$

For finding the regulating resistance R (Fig. 79), we use the open circuit characteristic of the motor (see Fig. 80). If I is the open circuit characteristic, then at a speed n a magnetizing current c is required to produce a voltage E_b. Neglecting the armature reaction, which in the most unfavourable case only amounts to 5 per cent., we find the new exciting current c_1 required to produce E_b from a curve II, which is obtained from curve I by the equation

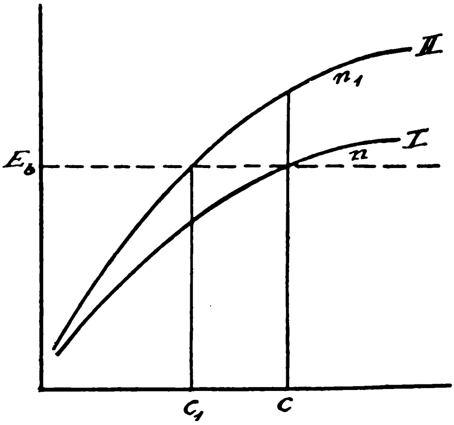

FIG. 80.

$$E_b = E_b' \frac{n}{n'}$$

For E_b we have again—

$$E_b = E - (C - c)r_a \quad . \quad . \quad . \quad (33)$$

Now, $R = \frac{E}{c} - r_s$, where c is found as described above.

Since an accuracy of 10 per cent. is hardly necessary with speed regulation, and, further, since C (formula 33) varies according to the load, we can make $E_b = E$.

Regulation of speed above the normal in series motors is also effected by weakening the field. In this case an open circuit curve is also required, and neglecting the ohmic loss and the armature reaction, the back E.M.F. in the armature $E_b = E$. For different speeds

$$E_b = E_b' \frac{n}{n'}$$

The magnetizing current c_s is found, as in the case of the shunt motor, and the resistance of the regulator to be put in parallel with the magnets (Fig. 72) is found from the following equations :—

$$c = c_s + c_2$$
$$e_s = r_s c_s$$
$$e_s = c\left(\frac{r_s R}{R + r_s}\right)$$
$$R = \frac{r_s e_s}{c r_s - e_s}$$
$$R = \frac{r_s^2 c_s}{c r_s - c_s r_s}$$

The increase of speed of three-phase motors is effected by decreasing the number of poles, but it requires more or less complicated connections. The synchronous speed of a three-phase motor $n = \frac{f\,60}{2p}$, where f stands for periodicity of the alternating current, and $2p$ for the number of poles. This formula shows clearly that to increase the speed n the number of poles $2p$ must be decreased.

CHAPTER VI

CONSTRUCTION AND CONNECTIONS OF REGULATORS FOR GENERATORS AND MOTORS

THE rules given in Chapter IV. for the fixing of coils and the arrangement of levers and contacts of starters apply also to regulators. With shunt regulators the current is usually smaller than in the case of starters; hence very frequently circular contacts, K, are employed, as in Fig. 81. In order to make the contact plate with

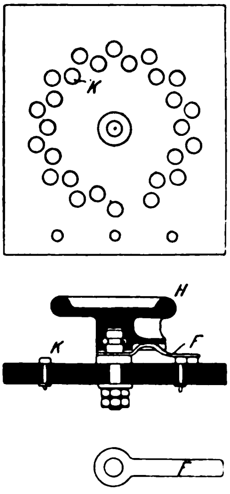

FIG. 81.

a large number of contacts as small as possible, the contacts are arranged in two rows. A handwheel, H, is often used instead of a lever; it is made of insulating material, and is made just large enough to be comfortably grasped in the hand. The arrangement of the stamped contact lever F and its connection with the handwheel are shown in Fig. 81.

Shunt regulators for motors are similar to those for generators, except that the former generally have less contacts.

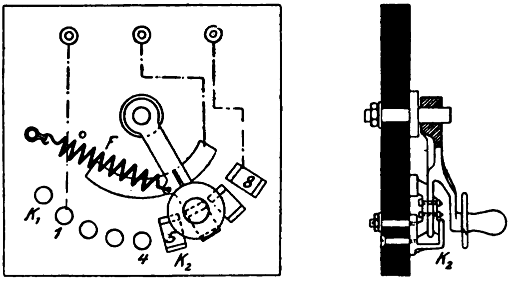

FIG. 82.

Two types of series regulating resistances for reducing the speed below the normal are shown in Figs. 82 and 83.

The first steps of the starter between 1 and 5 are designed to carry the current for a short time, the coils between 5 and 8 are designed to carry the current permanently, to regulate the speed by consuming part of the voltage. To prevent the starting-lever from stopping on contacts 1 to 4 (which would cause the coils to be burnt out), a spring, F, is provided, which tends to pull the lever back to K_1, unless it is on either of the contacts 5 to 8. These contacts are U-shaped, and therefore offer so great a frictional resistance to the pull of the spring that it is unable to pull the lever back.

The type shown in Fig. 83 is designed with the same object. In this regulator, also, the steps between

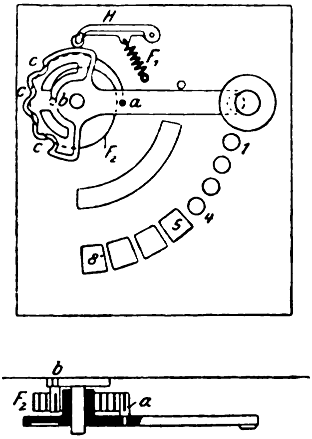

FIG. 83.

1 and 5 are designed for starting, and hence for a temporary load, while contacts 5 to 8 are designed for regulating. The lever projects backwards in the shape of a disc, provided with notches, *c*. Until the lever reaches contact 5, the small wheel on H does not catch the notches *c*, and so spring F_2 pulls the lever back. When the lever reaches contact 5, spring F_1 pulls the pawl H into notch *c*, and prevents the lever from being pulled back. By this arrangement the lever is always kept directly on one of the contacts, and can never stop on two contacts at the same time.

By a small addition, the starter shown in Fig. 83 can be provided with a no-voltage and an automatic overload release. The connections must be made as shown in Fig. 43. The magnet m_1 does not act on the lever as in Fig. 43, but attracts the pawl H (Fig. 83). The construction of the pawl for this purpose is shown in Fig. 84. The wheel R is arranged on a special lever, which is pressed down by a spring F_1.

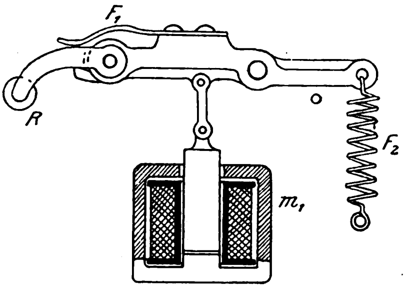

FIG. 84.

When the magnet m_1 is not excited, the spring F_2 lifts the left half of the lever, so that in case of a break in the exciting current, the motor is prevented from running away; since magnet m_1 does not act against the spring F_2, the lever is lifted from the notch *c* on the lever disc (Fig. 83), and the starting-lever is drawn back to its off position. When we start the motor, magnet m_1 is immediately magnetized, and pulls the lever down. The lever on which the wheel R is fixed presses against the disc, and in so doing puts tension on spring F_1. On moving the starting-lever until it reaches one of the permanent contacts, spring F_1 presses

R into the corresponding notch on the disc, and the lever is held fast. If an overload release is required, we must provide another magnet, m_2, which short-circuits m_1 at a pre-arranged overload.

In connection with appliances for regulating the speed of motors, we may describe a controller for the

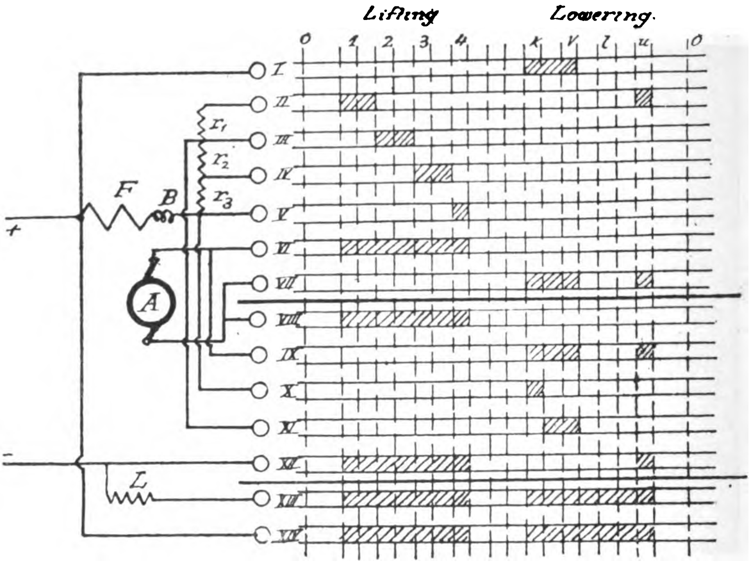

FIG. 85.

lifting motor on a travelling crane (Fig. 85). With regard to its construction, this controller corresponds to the one shown on Fig. 31. On position 0 the motor is switched off. On turning the cylinder to position 1 under the contact springs I, II, etc., the current enters the magnet winding F of the motor, passes through the magnetic blow-out B, the starting resistance r_3, r_2, r_1, contact II to VI, armature A, VIII, XII, and back to the negative supply. From the positive supply the current branches down to contact XIV to XIII, through the brake magnet coil L, to negative supply. This magnet lifts the brake which acts on the rope drum. On positions 1 to 4, the motor lifts the load, the starting being effected as usual by the cutting out of the resistances r_3, r_2, r_1, until it gets full voltage on position 4. During the whole time that the controller is on steps 1 to 4, the magnet L of the brake must be in circuit. On *u*, *l*, *v*, *k* the lowering of the load takes place. On these positions, also, the magnet winding L is in circuit. If the load is very small or the empty hook is to be lowered, then the lever is turned to stop *u*. With the controller in this position, the motor is in series with all the starting resistance, but it runs in the opposite direction to that which it does on positions 1 to 4. The reversal of the rotation is effected by reversing the armature current. If there is a load on the hook so that it will go down by its own weight, then the cylinder must be turned to position *l*; the motor is then not in circuit at all, but current flows through the magnet coils L. If the load happens to be so heavy, that it would lower too fast, then the motor must be braked; this can be done on steps *v* and *k*. On step *v* the motor is working as a dynamo on part (r_2 and r_3) of its starting resistance, and the energy of the descending load is transformed into heat. On *k* the motor is short-circuited, as a series generator consumes under this condition the maximum load. In making the connections, care must be taken to have the magnets of the motor when running as a generator connected so as to get a current flowing through them always in the same direction. Since series motors are generally employed for lifting purposes, it will be necessary when braking to change the connections between armature and magnet coils.

In Fig. 86 the connections made by a controller for crane-motors are shown. We see from these diagrams that the current is never reversed in the magnet coils. On stop *u* the armature current is reversed, the impressed voltage acts in the direction indicated by the full arrow, the back E.M.F. of the armature acts in the direction indicated by the dotted arrow. In positions *v* and *k* the back E.M.F. is acting, and thus the

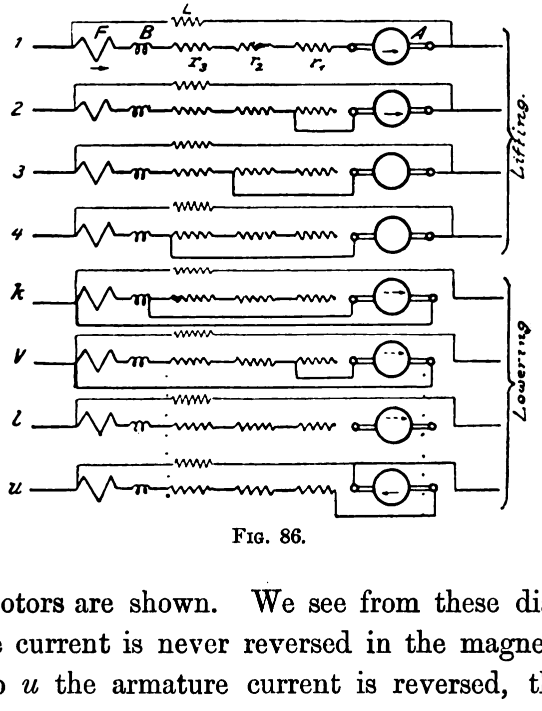

FIG. 86.

connections between armature and magnets must be made as in 1 to 4.

In braking shunt motors electrically, it is not necessary to change the connections between the magnets and armature, since the E.M.F. acting in braking (see dotted arrow, Fig. 87) sends a current through the

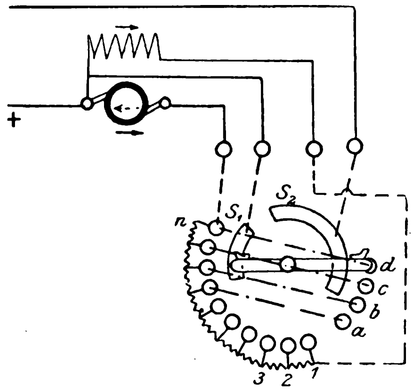

Fig. 87.

magnets in the same direction as the impressed voltage of the motor (see full arrow). Such a starter is shown in Fig. 87 : the lever is in the position on which there is the strongest braking effect—that is, the armature is short-circuited. The magnets are connected directly to the armature. Since with short-circuited armature the voltage exciting the magnets is but small, it is necessary for the lever to be turned quickly to contact *d*, so that the motor field is still strong enough to produce sufficient E.M.F. in the armature. The contacts *a*, *b*, and *c* are only for lessening the shock caused by suddenly short-circuiting the armature.

This kind of connection for braking is sometimes necessary in the driving of printing-machines and similar work, in which the machine driven has to be stopped quickly. If a shunt motor has to be braked continually, the magnets must be permanently connected to the full terminal voltage.

With tramcar motors at least two controllers are required. The direction of rotation of the motors, if started by one controller, must be opposite to that if started by the other. If for any reason the car has to go in the opposite direction, the driver has to use the controller at the other end. It must be possible to brake with either of the controllers. If, for instance, the controller is on the "full speed" position (Fig. 88, position 3, motor without resistance), and it is necessary to brake suddenly, the handle must be turned through the positions 2, 1, 0 to I or II. On position I the motor works as a generator on its starting resistance r_1 in parallel with r_2; on position II the armature is

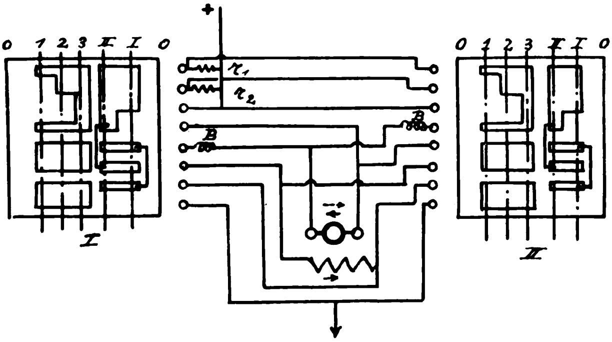

FIG. 88.

directly short-circuited. The starting resistance is in Fig. 88 reduced by a parallel connection; thus, on position 1, r_1 only is in series with the armature; on position 2, r_2 is put in parallel with r_1. For braking, the connection between armature and magnets has again to be changed, since series motors are employed in this case. Each controller is also provided with a magnetic blow-out, which is best connected in the armature circuit, as this is switched in in all positions. The starting resistances must be designed for overload. In going down gradients the handle will, according to the amount of incline, be turned to position I or II.

With tramcars usually two motors are employed, an arrangement which also simplifies the connections. In starting, both motors are connected in series, each of them being connected with half the voltage only; this will reduce both the size of the starting resistance and the energy losses in the starting resistance. For higher speeds, the motors are connected in parallel, each of them getting full voltage.

The starting arrangements for auto-cars are similar to those for tramcars. Here two motors are also generally employed, each of them driving one of the car wheels. The connections for full speed and braking are shown in Fig. 89.

On the running position 1 the motors A are connected in series with their magnets F and the resistances r_1 and r_2; on position 2 the resistances are short-circuited. On position 3 the motors are in parallel, and in series with the resistance r_1; on position 4, r_1 is short-circuited, thus the motors run at full speed. For braking, the handle must be turned backwards through 3, 2, 1, 0, to I or II. In position I the motors are working as generators on the resistance r_1 or r_2, with the connection

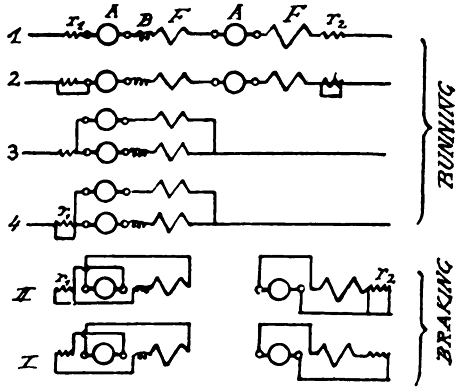

Fig. 89.

between armature and magnets changed ; on position II, the motors are short-circuited.

With the controller in Fig. 90, all these connections can be effected by turning the big cylinder I. In order to reverse the direction of rotation of the motors in an auto-car, the direction of either the armature or magnet current must be reversed. The latter can be effected in Fig. 90 by cylinder II. Both cylinders could be combined in a single one, but this would have several disadvantages. Firstly, the cylinder would have to be very long ; and, secondly, the movements for the various running positions could not be effected in such a simple way. With the connections shown in Fig. 90, the lever for turning the cylinder I can be arranged so that, for running forward, it must also be turned forward, and *vice versâ.* When it is necessary to apply the brake suddenly, the lever must be turned through the positions 3, 2, 1, 0 to I or II. In order to reverse the direction of running, cylinder I must always be in the off position; thus, cylinder II must be prevented from turning as long as cylinder I is switched in. An arrangement with this object is shown in Fig. 91. The controller is fixed horizontally beneath the driver's seat. The axis of cylinder I is marked a, that of cylinder II. b. Lever H_1 is provided with a disc having a slit, S, and a toothed quadrant, Z. By turning the lever H_1, cylinder I is switched in. Cylinder II can, however, only be turned when H_1 is in the "off" position, for only in this case can lever A be brought from position 1

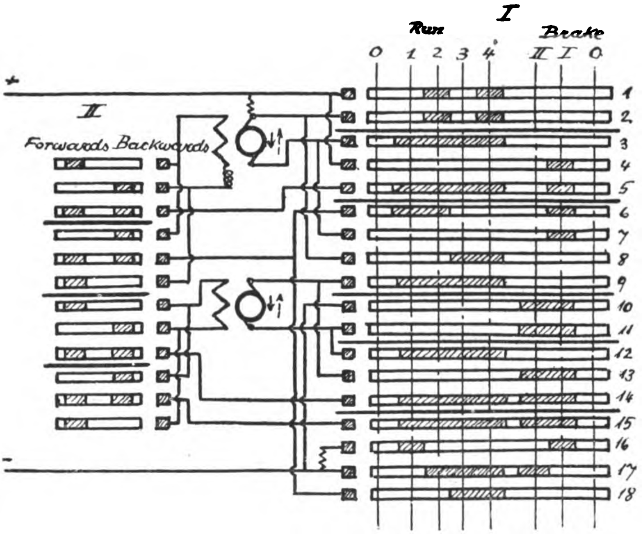

FIG. 90.

into position 3 by means of the handle H_2. By providing a rib, R, on the lever H_2, the latter can only be taken off while in the off position; lever A is then occupying the position 2, thus preventing the

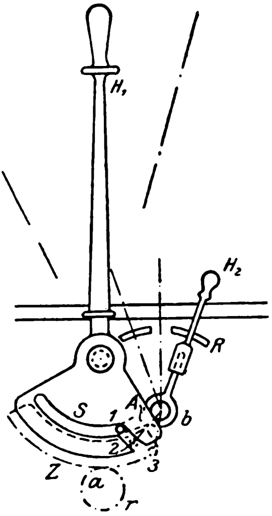

FIG. 91.

main lever H_1 from turning, so that the motors cannot be switched in. On leaving the car, the driver has always to take off H_2, thereby locking the controller.

The cylinder II in Fig. 90 is for changing the magnet connections for reversing the direction of rotation of the motors; there is no objection to this, as the changing is only done when the motors are stopped.

Connections

With shunt-wound generators the destructive effect of the E.M.F. of self-induction caused by breaking the field-magnet windings can be avoided by various means. One method is shown in Fig. 92. A resistance, r, is connected in parallel with the field-winding r_s. When the lever of the shunt regulator R is on any contact between 1 and n, the resistance r is not in circuit. To break the shunt circuit, the lever must be turned to 0. The contact surface on the lever must be sufficiently wide to cover 1 and 0 simultaneously. The current produced by the E.M.F. of self-induction in r_s can then flow through r. The current flowing through r at the moment when the circuit is broken—

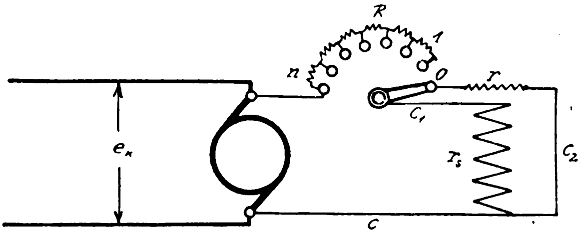

FIG. 92.

$$c_2 = \frac{e_k - cR}{r}$$

This method of connection is only applicable to self-excited machines, and if there is only one small machine, the whole plant being shut down by stopping this machine. With large machines this method of connection may sometimes be used for polishing or turning up the commutator, after the voltage has been reduced to zero; otherwise it is easier to turn the lever of the shunt regulator back, thus diminishing the current produced by the dynamo. As the main ammeter comes to zero the main lever is opened; the shunt regulator must, however, not be switched off before the engine is stopped. In this case no E.M.F. of self-induction is produced in the field windings at all, as the current in the field windings decreases simultaneously with the terminal voltage of the generator. In many cases there is an automatic cut-out in the main circuit; then the engine has only to be stopped, when, owing to the decreasing E.M.F. of the dynamo, the current will fall and the cut-out will break the circuit. When finally the machine is stopped, the lever of the shunt regulator may be turned to 0.

A method of connection for shunt-wound machines, which are sometimes self-excited and at other times separately excited, is shown in Fig. 93. (This may be the case if the machine sometimes runs alone and sometimes in parallel with other machines.) If the machine is to be self-excited, switch II must be closed; then, on turning the lever of R to the left, the machine will rise to its full voltage; then switch I is closed. For separate excitation, I is closed first (then the machine attains its full voltage quicker), and when the machine voltage is equal to the bus-bar voltage, switch II is closed; the generator may then be loaded by turning the lever of R further to the left.

To stop the machine, the lever of the shunt regulator should be turned to the right until the generator does not supply any current; switch I must then be opened and the engine stopped.

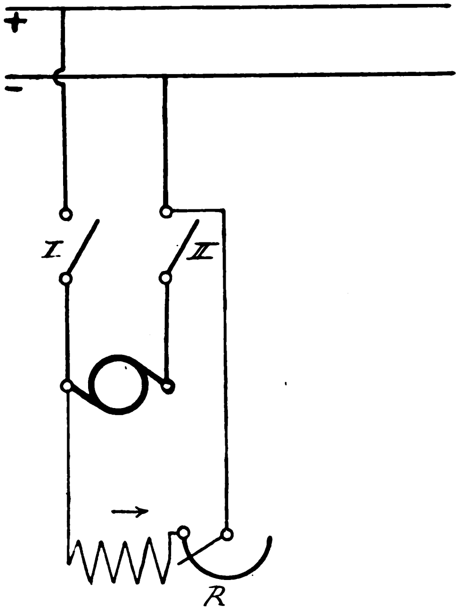

FIG. 93.

Series generators for power transmission can be shut down by simply stopping the engine. They are sometimes provided with an overload cut-out, as shown in Fig. 72. If the current becomes excessive, then the magnet *m*, which is excited by the main current, attracts its armature, so that the lever H short-circuits the magnet winding r_s. The generator loses its field, and therefore its voltage.

An automatic regulator for shunt-wound dynamos is shown in Fig. 94. The single contacts of the shunt regulator R are connected to wires which gradually decrease in length, and which dip into a vessel H*g* containing mercury. This vessel is fixed on an iron core, which projects into the magnet. When there is no current flowing in either of the two windings, the counter-weight will lift up the iron core, and all the ends of the wire will dip in the mercury, hence R will be short-circuited. When the machine is started it will excite itself, and the terminal voltage produced will send a current through S_2, which, if the voltage is normal, is sufficient to pull the core right down, so that all the resistance R is in series with the field-coils. When the terminal voltage is normal, the generator is loaded. A branch current *c* of the main current C is then flowing

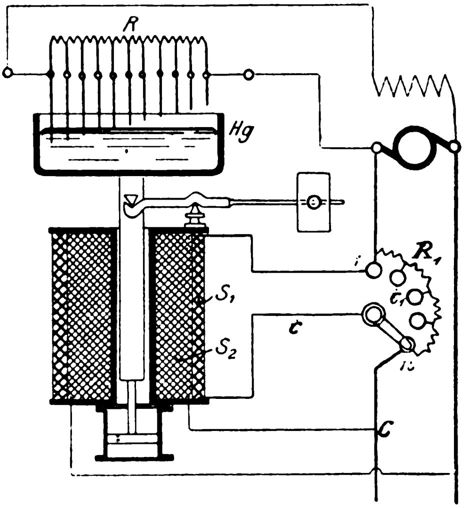

FIG. 94.

through coil S_1. Let the resistance of the latter be r_1. Then

$$c = \frac{c_1 R}{r_1}, \; C = c + c_1, \; c = \frac{(C - c)R}{r_1}$$

For normal working, the position of the lever of the resistance R_1, which is only very small, and designed to carry the full main current, is on contact n. When the generator is at maximum load, the effect of the ampere-turns of the thick wire coil S_1 is exactly counterbalanced by that of the thin wire coil S_2. Thus the counter-weight lifts the iron core up, and all the resistance R is short-circuited. The smaller the load the smaller will be the action of S_1, and the lower the position of the mercury vessel will be. If for running in parallel the load of the machine is to be altered, the lever must be turned from n towards 1, the voltage $(C - c)R_1$ producing c will be zero. Thus, for stopping the generator the lever must be turned to 1, so that R is in circuit, as then the thin wire coil S_2 only is effective, and the current C falls. The switch connecting the dynamo with the bus-bars may be opened as soon as $C = 0$. For damping the motion, the iron core is fitted with a piston, which moves in a cylinder filled with glycerine.

With electric motors regulators are used for regulating the speed. The regulation below the normal speed having been dealt with already, it is necessary to describe briefly the regulation of speed above the normal, which, as mentioned already, can be effected by weakening the motor field.

Fig. 95 shows a useful method of connection for a combined starter and regulator. Lever A is used for starting the motor, lever R for regulating the speed. With the lever R on stop r_o', the normal current $c_s = c$ flows through the field winding. By turning R towards r_n' the field current c_s is weakened. The coils of the starter must be designed so that they can carry the current c_2 permanently. Let R be that part of the starter which is employed for speed regulation, then the voltage lost in the branch circuit between a and b is

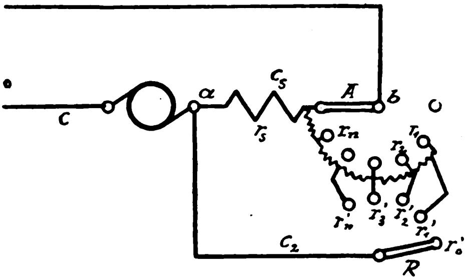

Fig. 95.

$$e_v = c\left(\frac{r_s R}{r_s + R}\right)$$

and

$$c_2 = \frac{e_v}{R}$$

Series motors with regulation above the normal speed are seldom employed, except sometimes for tramcars. Otherwise series motors are generally used for cases where the torque to be developed is constant, as, for instance, in the case of pumps. If the motor is speeded up it pumps more water; thus its output is increased. As the terminal voltage is constant, the current C must increase. This will be clear from the following consideration. With a pump the torque is constant; the torque of a motor is directly proportional to the strength of its field and the armature current. As the former decreases, the latter must increase. This must be considered in determining c_2.

In the case of shunt motors, the field current is weakened by inserting resistance in the shunt circuit. Fig. 96 shows a method of connection patented by the Electrical Company. R is a starter, the lever of which connects the contacts with the quadrant s_1. The latter is connected with the first starting contact, so that the motor can be switched off without sparking. By turning the lever to the last contact S_2, which forms a sliding contact, S_1 and S_2 are connected with each other, and the motor is running at normal speed. On turning the lever further to the right, the resistance R_1 is switched in series with the field coils.

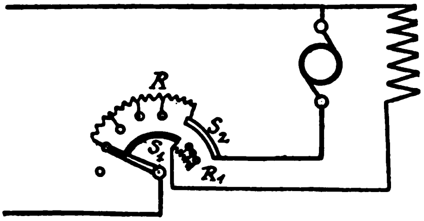

FIG. 96.

In Fig. 97 there are two levers, one (H_1) is the starting, and H_2 the regulating, lever. The latter is insulated from the former, and connects quadrant S with the stops r. In switching off, H_1 takes H_2 with it, moving it to stop r'_1. This arrangement has the advantage that, in starting, the motor field is always at its maximum strength; hence the starting torque will be large. The motor is thus easily started.

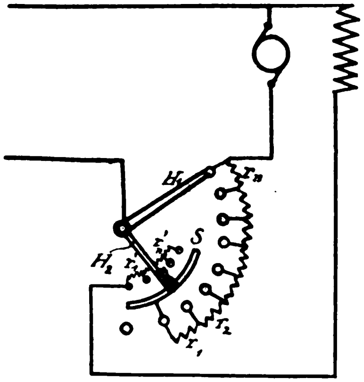

Fig. 97.

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